

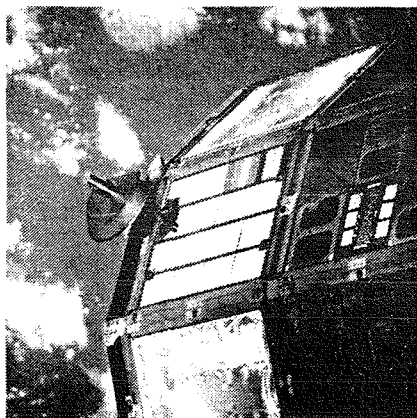
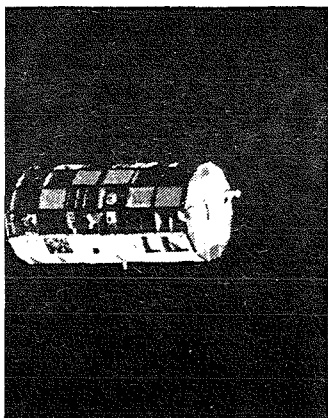
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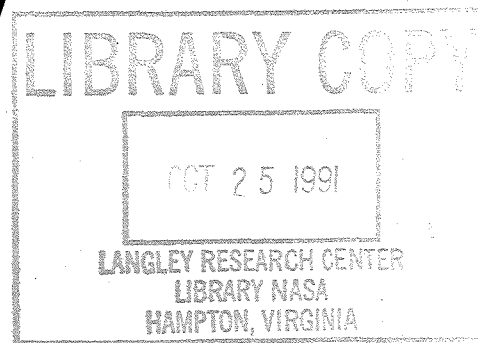


Long Duration Exposure Facility

Systems Special Investigation Group

Interim Report

January 1991



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BOEING SYSTEM SIG CORE TEAM

The System SIG activities at Boeing have been divided into five engineering disciplines; Electrical, Mechanical, Optics, Thermal, and Batteries/Solar Cells. Specific Boeing individuals have been assigned the responsibilities for activities that fall within each area. These individuals are shown on the accompanying chart. The specific tests that fall within each discipline are described in the LDEF Systems Special Investigation Group Plan (Ref 1). In general, the efforts of the System SIG will concentrate at the highest possible level of assemblage of subsystems and/or components to detect functional changes, degradation and/or failures. Failure analysis and further lower level testing will then be conducted.

All LDEF hardware has been categorized by the Systems SIG into either Experimenter Systems or LDEF Systems. LDEF Systems are defined to be the hardware provided by the LDEF Project Office which performed a functional role during the LDEF mission in support of the experimenter's objectives. The Experimenter Systems are the hardware provided by the experimenter which performed a functional role in support of the experimenter's objectives. The majority of the hardware tested at Boeing and/or reported on in this document are LDEF Systems hardware. Data from testing of individual experimenter's hardware will be collated into the System SIG database as the test reports are received.

Reference 1: Mason, J. B., Edelman, J.E., Dursch, H. W., LDEF Systems Special Investigation Group Investigation Plan, February 1990.

BOEING SYSTEM SIG CORE TEAM

- Core Team Leader - Harry Dursch
 - Electrical - Emmett Miller
 - Mechanical - Dr. Steve Spear
 - Optics - Tim Majoch
 - Thermal - Dr. Wally Plagemann
 - Batteries/Solar Cells - Dr. Chris Johnson
- Responsibilities include:
 - Support de-integration at KSC
 - Testing of hardware at Boeing
 - Review of PI test plans & test results
 - Support of test activities at PI labs
 - Collation of all test results into SSIG handbook/database

LDEF ENVIRONMENT

LDEF was retrieved on January 12, 1990 after 70 months of exposure to LEO. LDEF was in a constant orientation relative to the RAM direction throughout its entire mission. This resulted in an excellent opportunity to map the effects of the various space environments on the systems and materials flown on LDEF.

Representative temperatures shown on this chart are from two of the seven temperature sensors mounted on various locations on the LDEF internal structure. These temps are the max and min for the first 390 days of flight (Ref. 2). Don Wilkes reports that one of the batteries mounted on the backside of his experiment (tray A9) had a max temp of 81°F and a min of temp of 57°F over the first 600 days of the mission.

The LDEF hardware located on the inside of LDEF was shielded from the UV radiation and atomic oxygen. Most electrical hardware was mounted on the interior and, therefore, saw a relatively benign space environment.

The hardware mounted on the exterior surfaces was exposed to a variety of temperature, meteoroid and debris, UV radiation and atomic oxygen environments, dependent of its specific location and absorptance/emittance ratio

Reference 2: Berrios, W. M., Long Duration Exposure Facility Post-Flight Thermal Analysis, Orbital/Thermal Environment Data Package, October, 1990, NASA LaRC.

Reference 3: See, T. et.al., Meteoroid and Debris Impact Features Documented on LDEF, August 1990, NASA JSC.

Environment Seen by LDEF

- Recovered from LEO after almost 6 years
- Non-oscillatory attitude
- Benign temperature environment
 - Interior surface temperature:
 - Earth end; 105°F max, 46°F min
 - Space end; 96°F max, 41°F min
- Atomic oxygen flux vs time
 - Function of increasing solar flares and decreasing orbit
- Meteoroid and space debris
 - ~ 3100 impacts > 0.5 mm (Ref. 3)
- Ultra-violet radiation
- Thermal cycling
 - ~ 34,000 orbits

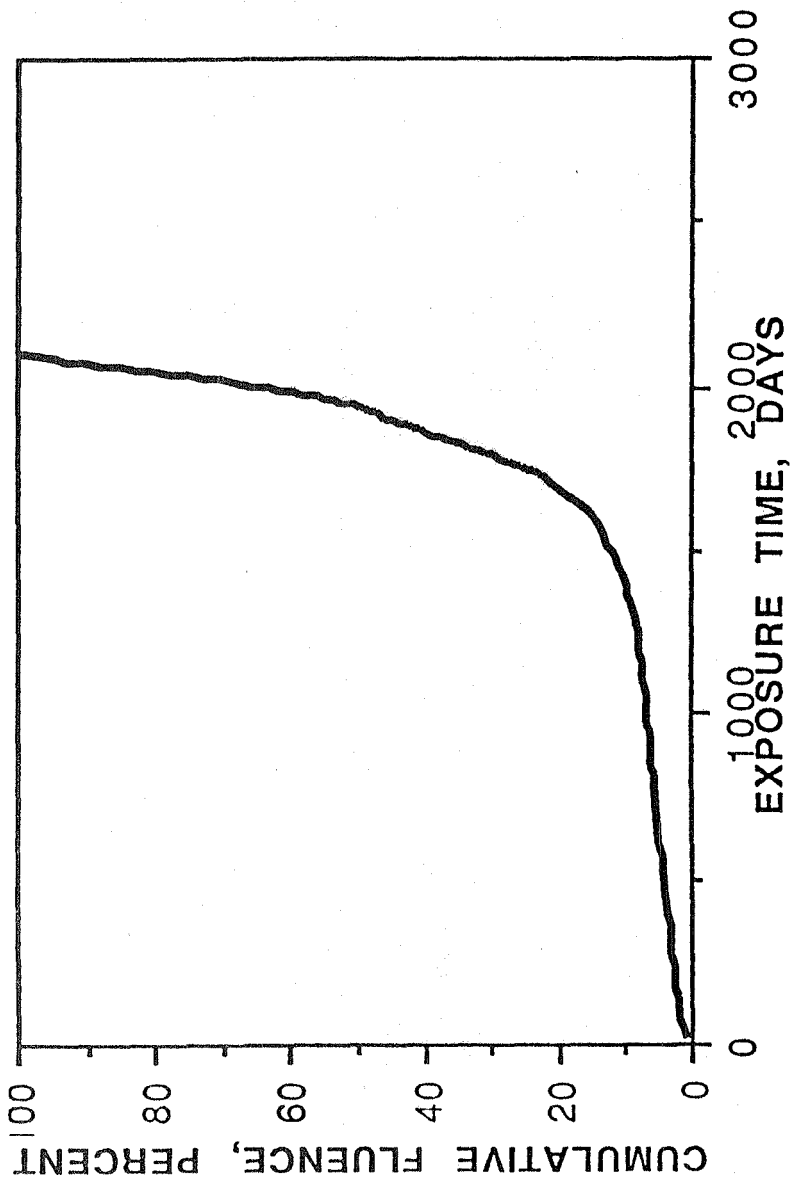
LDEF ENVIRONMENT, ATOMIC OXYGEN

The following chart shows the cumulative atomic oxygen fluence vs time for the LDEF mission (Ref. 4). The decaying orbit near the end of the mission and the increasing solar activity (the end of the LDEF mission occurred near the peak of the 11 year solar cycle) caused the atomic oxygen flux to increase rapidly near the end of the mission. It is particularly significant that after almost four years into the LDEF mission, LDEF had received only 9% of its total atomic oxygen exposure; and that in the last year of the mission, LDEF received 78% of its atomic oxygen exposure.

The environmental exposure control canisters (EECC) were opened 10 days after deployment of LDEF and then closed 10 months later. The specimens within the EECC's saw only ~3% of the total atomic oxygen fluence seen by adjoining hardware of LDEF.

Reference 4: Bourassa, R. J., Gillis, J. R., Atomic Oxygen Flux and Fluence Calculation for Long Duration Exposure Facility, August 13, 1990. (This activity was accomplished under Boeing's support of the Material's Special Investigation Group and is available upon request).

LDEF, CUMULATIVE PERCENT ATOMIC OXYGEN
FLUENCE VS EXPOSURE TIME

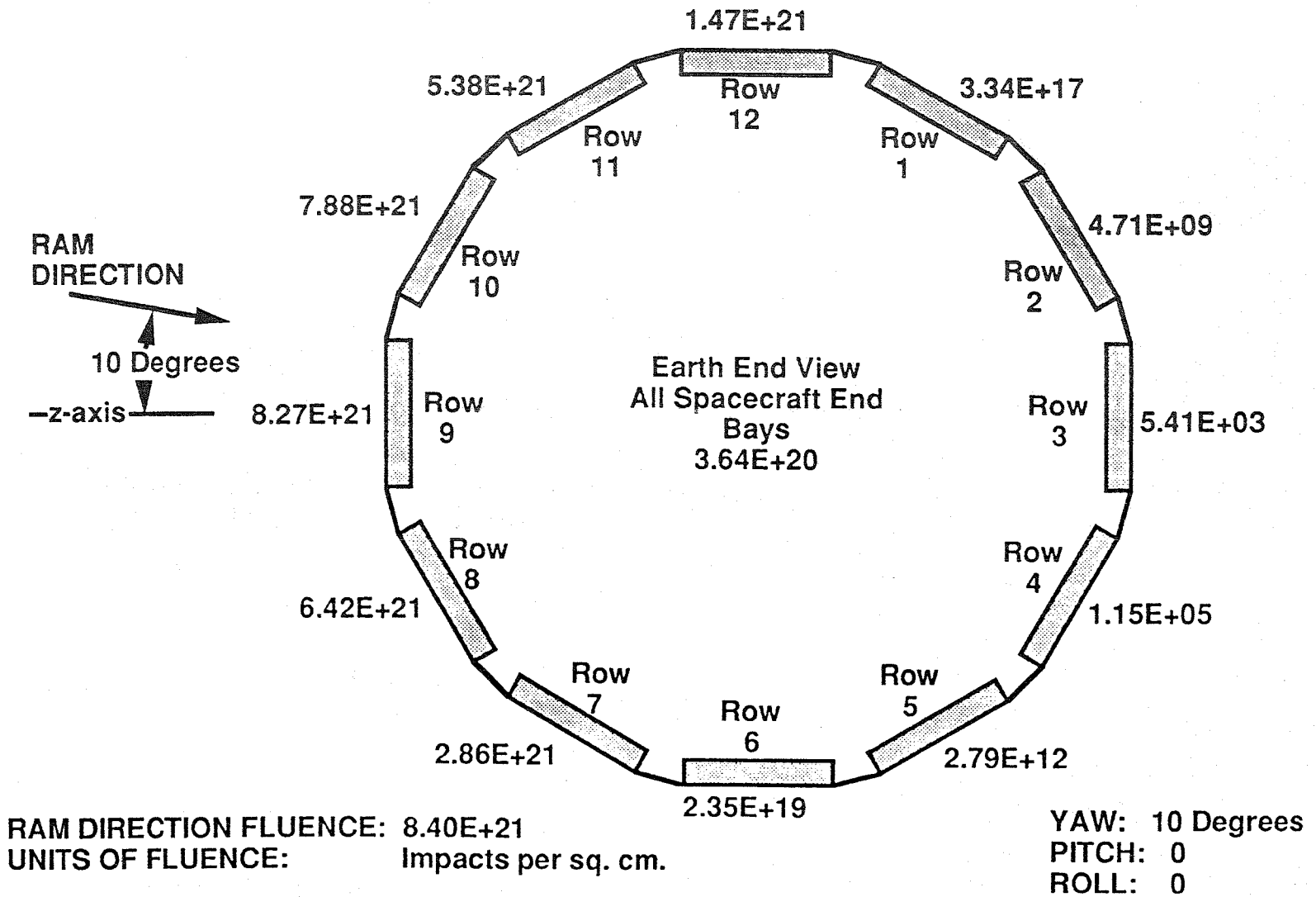


ATOMIC OXYGEN FLUENCE FOR EACH TRAY LOCATION

The angle of incidence for each LDEF surface was fixed by its unique geometry and constant flight angle. Several independent methods have indicated yaw for LDEF was somewhere between 7 and 12 degrees. A yaw angle of 10 degrees was selected for the calculations shown on this chart.

The calculated fluence for the ram direction is $8.4/10^{21}$
atoms (impacts)/cm²

ATOMIC OXYGEN FLUENCES FOR EACH TRAY LOCATION



LDEF DEINTEGRATION

On-site support of the deintegration was provided from January 27, 1990 through May 4, 1990. The following chart summarizes the activities.

Deintegration of LDEF at KSC

- On-site Boeing support starting with LDEF removal from Columbia (1/27/90) through completion of deintegration (5/4/90)
- Primary responsibility was to represent Systems SIG interests during deintegration
 - On-site functional testing of LDEF and PI's hardware
 - Discussions of test plans with PIs
 - Developed initial hardware testing prioritization
 - Assisted in development of MOU's with PIs
 - Packaging and shipping of selected hardware to Boeing

Systems SIG Preliminary Findings

The following three charts summerize the Systems SIG findings to date. Each finding is discussed in further detail within this report.

SYSTEMS SIG PRELIMINARY FINDINGS

- NO ELECTRICAL OR MECHANICAL SYSTEM LEVEL FAILURES ATTRIBUTED TO THE LEO SPACE ENVIRONMENT HAVE YET BEEN DETECTED
- MOST SYSTEMS WORKED: RELATIVELY FEW FAILURES OCCURRED
 - LEO CONDITIONS PERMIT HIGH RELIABILITY/LONG TERM USE IF SYSTEMS ARE PROPERLY DESIGNED, MANUFACTURED, INTEGRATED, TESTED, AND SHIELDED
 - PRACTICAL LOW COST/HIGH RISK SPACE FLIGHT SYSTEMS WERE DEMONSTRATED
- SOME LOW COST ELECTRICAL/ELECTRONIC COMPONENTS WERE USED SUCCESSFULLY
 - MAY BE POSSIBLE TO RELAX SOME RULES UNDER BENIGN CONDITIONS, IF PROPER TESTING, BACKUP SYSTEMS, AND SHIELDS PROVIDED (THERMAL, RADIATION, ATOMIC OXYGEN, DRIFT)
 - ADDITIONAL STUDY REQUIRED

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SYSTEMS SIG PRELIMINARY FINDINGS (CONT.)

- EXTENSIVE CONTAMINATION AND MATERIAL DRIFTING, CONDUCTIVE MATERIALS ARE A POTENTIAL HAZARD: EXPOSED SENSORS, HV TERMINALS VULNERABLE
 - ADDITIONAL CONTROLS ON ALLOWABLE MATERIALS, AND ENCLOSURES TO CAPTURE (OR EXCLUDE) LOOSE MATERIALS MAY BE REQUIRED
 - EMPHASIZE CONTAMINATION CONTROL
- ELECTRICAL RELAYS ARE A CONTINUING PROBLEM AREA
 - USE QUALIFIED VENDORS
 - INDIVIDUAL PART SCREENING AT LIMITS OF SPECIFIED VOLTAGES, PULSE WIDTHS, TEMPERATURES, VIBRATION, ETC.
 - REDUNDANCY
 - ALTERNATIVE SWITCH TYPES IF FEASIBLE

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SYSTEMS SIG PRELIMINARY FINDINGS (CONT.)

- NO EVIDENCE OF COLD-WELDING DUE TO SPACE EXPOSURE
- DIFFICULT FASTENER REMOVAL APPARENTLY RELATED TO GALLING DAMAGE DURING INSTALLATION
 - INTEGRATION PROCEDURES MUST BE SCRUTINIZED
 - STAINLESS STEELS ARE VERY SUSCEPTIBLE TO GALLING
 - SUCCESSFUL APPLICATION REQUIRES HIGH THREAD QUALITY AND APPROPRIATE LUBRICATION SCHEMES
 - ADDITIONAL STUDY REQUIRED
- NO BULK METALLURGICAL CHANGES IN ALUMINUM OR TITANIUM MATERIALS DUE TO SPACE EXPOSURE
- VISCOUS DAMPER DEMONSTRATED AS VIABLE ATTITUDE CONTROL SYSTEM FOR SPACE STATION SEGMENTS

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Anomalies - LDEF Systems

This chart lists the major anomalies possessed by the various LDEF systems. The results, to date, from testing and analysis to understand the cause and effect of these anomalies, are discussed within this report.

ANOMALIES LDEF SYSTEMS

PRIMARY STRUCTURE

END SUPPORT BEAM AND KEEL TRUNNION
TRAY CLAMPS

GALLING OF MATING SURFACES
CHANGES IN CHROMIC ACID ANODIZE ALUMINUM

EASTENERS

TRAY CLAMP FASTENERS
PNEUMOLIC SPACERS
WASHERS
EXPERIMENT FASTENERS

EXTENSIVE GALLING, SEVERE THREAD DAMAGE
DIMENSIONAL CHANGE / LOW REMOVAL TORQUES
BONDED TO BASE PLATE
GALLING, BONDING, SHEARING

ENVIRONMENT EXPOSURE CONTROL CANISTER (EECC)

ALL FIVE OPENED

MECHANISM SPEED VARIATIONS
ATMOSPHERIC PRESSURE IN TWO UNITS

BATTERIES

LISO₂
LICF

ONE LEAKING CELL
DIMETHYL SULFATE GAS LEAKS

MAGNETIC TAPE MODULE (MTM)

S 0014
S 0069
M 0003
FIVE OF SEVEN UNITS

SIGNS OF VIBRATION ON TAPE
RELAY MALFUNCTION
POSSIBLE MOTOR BEARING NOISE
TAPE MECHANICAL SET

EXPERIMENT INITIATE SYSTEM (EIS)

RELAY

UNUSED STATUS INDICATOR DID NOT OPERATE

Anomalies - Experiment Systems

This chart lists the major anomalies possessed by the various Experiment Systems. The status of the failure analysis being performed on A0038 and A0187-1 is discussed on pages 57-70 and 71-74 respectively. All other anomalies are being investigated by the respective principal investigations. The System SIG will monitor this testing and analysis, provide assistance as needed, and document/report the results as they are received.

ANOMALIES EXPERIMENT SYSTEMS

A 0038	ONE RELAY FAILURE; SEVERE CONTAMINATION AND UNUSUAL PATTERNS ON ALL FOUR TRAYS; ONLY ONE OF 35 FOILS OPENED; FIVE OF SEVENTY MICRO- COULOMBMETERS (E-CELLS) LEAKED	A 0201	SUN SENSOR SATURATION; ERRATIC CMOS SENSOR DATA
A 0054	EVIDENCE OF ELECTROSTATIC DISCHARGE	M 0004	APPARENT "CORROSION" AROUND BOLT HEADS
A 0076	PREMATURE SHUTOFF (40 DAYS VS. 100 DAYS OF DATA)	M 0006	OUTER COVER BOLTS SHEARED DURING DISMANTLING
A 0133	ELECTRONICS ODOR; SHEARED BOLTS	S 0014	GULTEN POWER SUPPLY UNIT FAILURE DURING BENCH TEST
A 0171	SPECIMEN RETAINING HARDWARE FROZEN IN PLACE	S 0069	RELAY FAILURE; BINDING CAROUSEL MECHANISM; MALFUNCTION OF DEUTERIUM LAMP; CLOCK BIT LATCHUP
A 0175	SEVERE FASTENER GALLING	S 1001	DID NOT ACHIEVE LOW TEMPERATURE REQUIRED FOR OPERATION
A 0180	ELECTRONICS ODOR; LOSS OF TAPE OXIDE ADHESION IN DRY NITROGEN	S 1005	SIGNS OF INTERNAL MALFUNCTION; RADIATION SHIELDS CRACKED; MTM NOT STOPPED AS EXPECTED
A 0187-1	CLAM SHELLS WERE NOT CLOSED ON RETRIEVAL; INITIAL ATTEMPT TO CLOSE WAS UNSUCCESSFUL		

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INDIVIDUAL PRESENTATIONS

- Objectives
- Systems/components flown
- Tests performed and results to date
- Follow-on activities
- Preliminary conclusions

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Electrical

Emmett Miller

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ELECTRICAL OBJECTIVES

LDEF incorporated a considerable variety of electrical systems. Some were supplied by NASA, either as standalone units (e.g. Experiment Initiate System, "EIS") or to be utilized within experimenter's trays (Experiment Power and Data System, "EPDS"). Many other systems were designed and built by the experimenters, to a variety of specifications for part procurement and system test. These included many commercial quality parts, often with limited or no screening tests. In general, these were used for control and data collection purposes rather than as integral parts of the experiment. Therefore they were generally protected from direct exposure to the external environment, and are probably representative of similar systems used on many other spacecraft. The major differences between LDEF systems and those of other programs follow from the low cost approach utilized both by NASA and the experimenters, and the length of time systems were exposed to low earth orbital conditions. Examples of the low cost approach include the use of commercial or Class B components instead of Class S and the absence of thermal/vacuum testing on some of the hardware flown on LDEF.

OBJECTIVES

- Determine effects of LDEF exposure on electrical systems & components
- Evaluate performance of LDEF systems:
derive lessons learned

SUMMARY OF SYSTEMS FLOWN

The EIS was essential for turning on all active experiments, as no internal timers were utilized as backup. Although simple in concept, consisting of timers and sequencers to activate latching relays in the 24 experiments, it also incorporated feedback to latching visual indicators, including six on the LDEF exterior. These six were utilized by the astronauts during initial launch and activation to verify successful initiate operation.

The EPDS was the only NASA-supplied electronic system with multiple units flown at various locations on the spacecraft. Although programming (for types of input data and timing) varied between units, depending upon experiment requirements, all utilized the same logic, control and memory cards, and the same tape recorder.

The wire harness was assembled in place on the spacecraft, rather than being built and tested separately. Construction incorporated multiple TFE insulated wires and nylon cable ties, with connectors typical of current practice.

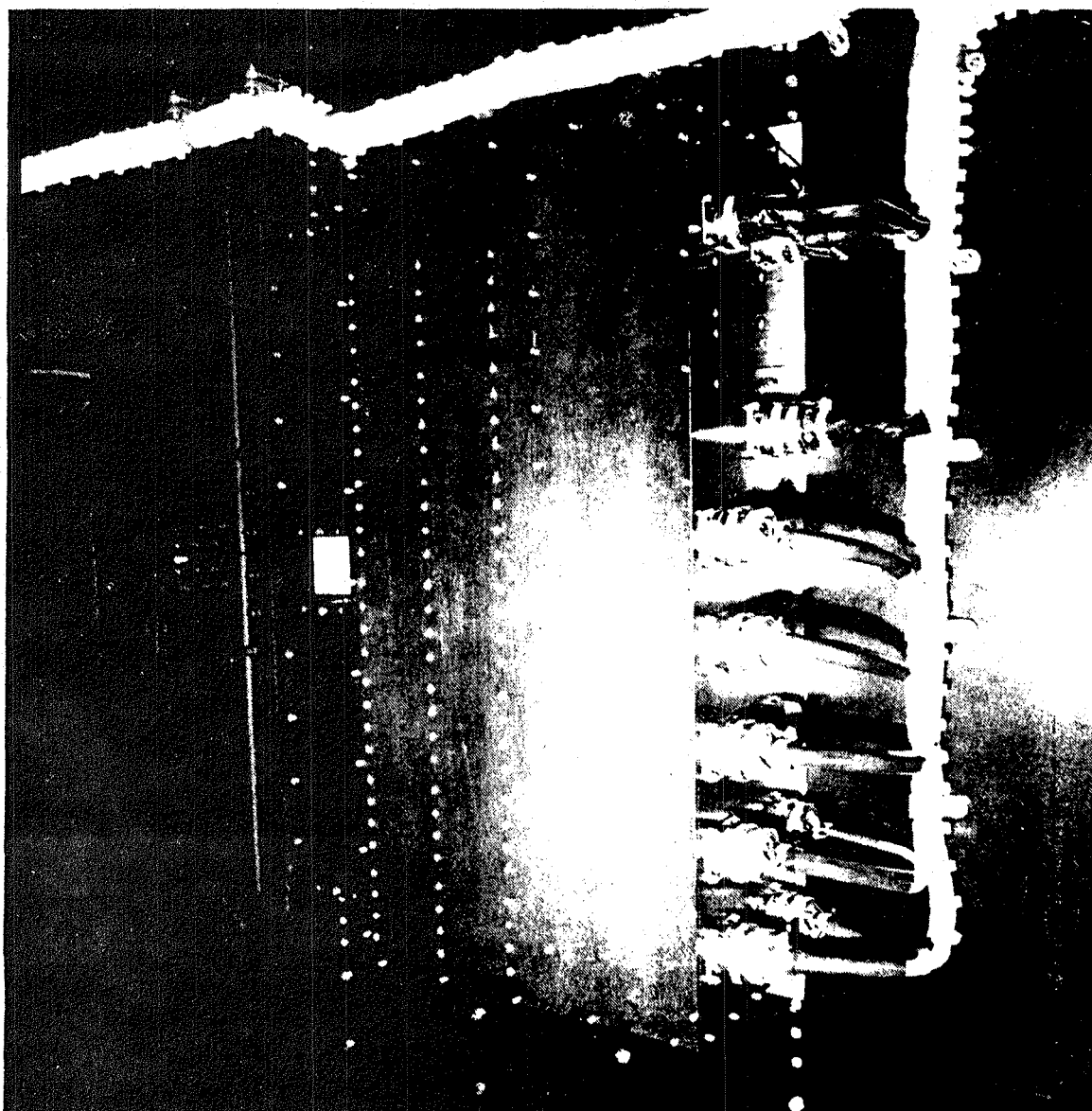
A number of experiments incorporated data collection and control systems, either to interface with the EPDS, or utilizing independant data storage units. These were designed by the experimenters or their selected contractors. Designs were reviewed by NASA for safety and absence of interference with other LDEF systems, but not for their ability to meet the experimenter's objectives.

SUMMARY OF SYSTEMS FLOWN

- Experiment Initiate System (EIS)
 - 1 system with 24 outputs to turn experiment timers on/off
- Experiment Power and Data System (EPDS)
 - 7 units flown (six experiments)
 - CMOS logic and memory: MIL-STD-883 Class B
 - Magnetic Tape Recorder (MTM)
- Wire Harness
 - EIS to all active experiments
 - Some inter-tray cabling
- Individual Experiment Systems
 - Many experiments contained systems or components of interest

THE EIS CONTROL BOX

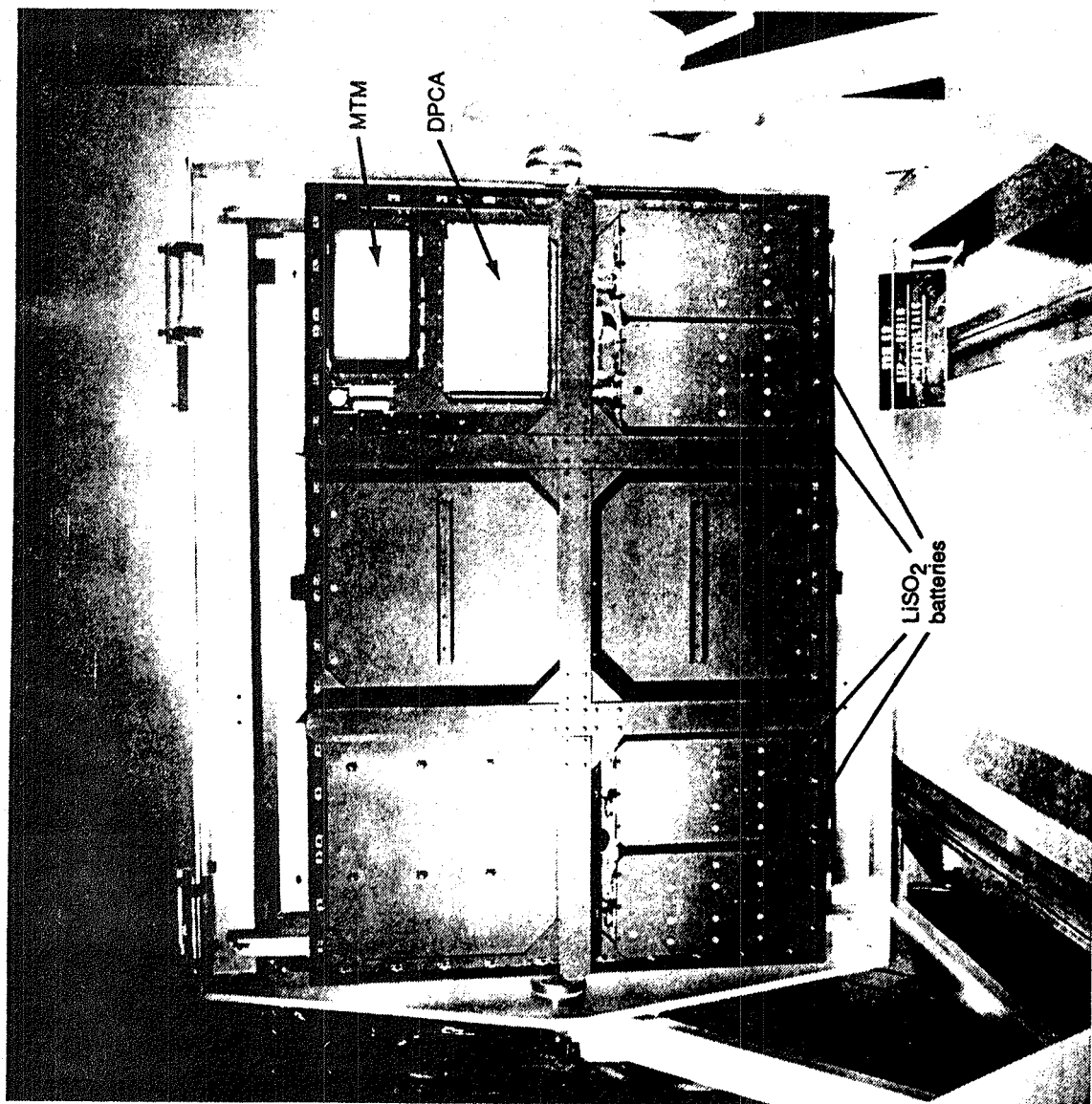
The EIS control circuitry was housed in this aluminum enclosure, located on the interior structure of LDEF. It was protected from direct exposure to the exterior by the LDEF frame structure and the experiment trays. The cabling shown is typical of the LDEF wire harness construction, with extensive use of tie wraps and clamps to the frame. Visual status indicators were located on the right side of the box (not visible in photograph).



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TYPICAL EPDS MOUNTING

The principal EPDS components are shown in the upper right corner of this tray, consisting of the DPCA (Data Processor and Control Assembly) and the MTM (Magnetic Tape Module). These, together with associated batteries, were mounted on a one-third-tray size plate, with the space side (hidden) protected with an aluminum and fiberglass shield.



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SUMMARY OF COMPONENTS FLOWN

These charts are included to give an overview of the very wide variety of electrical and electronic components utilized on LDEF. Since design and fabrication occurred in the late 1970's, some more recent part categories are not represented (e.g. large SRAM's, 16 or 32 bit microprocessors, etc.). However, the technology incorporated in many of the latest microelectronic components is represented in the LDEF components, and many of these are still in current use for new designs.

A more detailed list of hardware flown is available on request.

SUMMARY OF COMPONENTS FLOWN

- Microcircuits
 - Analog and digital (mostly MIL-STD-883, Class B, or commercial): CMOS, LS logic
- Discrete:
 - Relays, indicators, C's, R's
- Materials:
 - Circuit boards, conformal coatings, potting compounds, shields
- High voltage supplies: to 1kV
- Fiber Optics
- Optical Couplers
- Solar Cells
- Batteries: LiSO₂, NiCd, LiCF

DEINTEGRATION OBJECTIVES

Prior to and during deintegration at KSC, numerous activities took place under System SIG oversight. The objective was to assure that all information of potential value was recovered prior to any activities which might destroy such information. Emphasis was placed on documentation of the condition and operational status of LDEF and experiment systems as early as possible after LDEF was moved to SAEF2, and on providing guidelines to experimenters for inspection and testing during follow-on activities.

DEINTEGRATION OBJECTIVES

- Document condition and status of systems prior to removal:
 - EIS status indicators
 - Experiment initiate relays
 - High voltages off
 - Visual inspections
- Prevent inadvertent damage or undocumented changes:
 - ESD protection and handling
- Prevent loss of non-experiment data
 - Standard test plans
- Preservation of hardware
- Non-interference with experiment objectives

KSC TESTS AND RESULTS

The six external EIS status indicators had indicated successful experiment initiation at deployment in 1984. In a change to the original plan, the EIS was not reset at recovery, to prevent accidental or unpredictable effects associated with discharged batteries or the extended orbital period. An early activity at KSC was therefore to verify that all experiment initiate relays were still in the "SET" state (experiment turned on), and that the used status indicators on the EIS box were in their correct SET state. This was followed by thorough visual inspection in-place, and later by functional testing at KSC after removal from LDEF. The EIS apparently performed flawlessly during flight. The only significant anomaly observed was the failure of one unused status indicator to function the first time it was exercised. This is of concern due to the reliance on similar indicators to signal experiment turn-on during launch. Failure of any of the external status indicators would have caused considerable inconvenience and lost time in verifying initiation at that time.

Two of the EPDS units were exercised at KSC during testing of their associated experiments. Both appeared to function normally, although certain anomalies were observed which required later study at the experimenter's facility.

KSC TESTS AND RESULTS

- Experiment Initiate System (EIS)
 - Status indicators: all were SET
 - Experiment initiate relays: all SET
 - Cables and connectors: all nominal
 - Functional test: one unused status indicator failed first SET test
- Experiment Power and Data Systems (EPDS)
 - System functional tests, with EPDS current measurements
 - M0004: apparent anomalies, later explained (not failures)
 - S1001: normal operation (including solar arrays)

POST-DEINTEGRATION FINDINGS: EIS

The EIS control box was examined internally at NASA Langley Research Center. This was the first LDEF electronic system examined in this manner, and serves at a reference point for future examinations of EPDS units and others. No degradation or significant anomalies were observed on any of the internal components or circuit cards. Minor anomalies, including debris from initial assembly and a loose connector clamp ring, were observed, but these would not have resulted in any degradation of performance. However, they do point to the importance of meticulous handling and cleaning of space hardware. Obviously, debris which was electrically conducting (not observed in EIS) could cause major problems while drifting during weightlessness.

Failure analysis of the faulty EIS status indicator was performed at Boeing. The failing unit and others were tested under marginal voltage and pulse width conditions. This type of testing, at the limits of the manufacturer's specifications, is an effective means of detecting a variety of problems in electromechanical devices. The marginal voltage/pulse width testing confirmed the faulty operation, and internal inspection revealed a non-conducting particle which was the probable cause of failure. It is strongly suggested that similar marginal testing be performed at the part level on all such devices (100% of flight units) prior to future flight applications.

POST-DEINTEGRATION FINDINGS: EIS

- Internal inspection: no degradation
- Loose clamp ring on connector
- Failed status indicator: probable particle-induced intermittency, detectable by testing at low voltage, minimum pulse width

POST-INTEGRATION FINDINGS: EPDS

To date (October, 1990), only one of the seven EPDS units has exhibited any significant problems, and all performed satisfactorily during the LDEF flight. During testing at the M0003 experimenter's facility one of two EPDS units went into a continuous data record/tape record mode at the end of the first programmed record period. The other unit, similarly programmed, performed normally. This failure did not occur during flight, and flight data was not affected. Limited testing at the experimenter's facility did not reveal the cause of failure. The unit was shipped to Boeing. Failure analysis testing showed the problem to be an intermittent short in one of the GSE cable connectors, not in any of the flight hardware.

The apparent high standby current observed on the M0004 unit at KSC was traced to a previously unrecognized experiment turn-on operation when the EPDS was first activated by the EIS. This was caused by a pulse generated by the EPDS, and could have been eliminated by a minor circuit modification, as discussed in the "fine print" of the EPDS manual. No problems with experiment operation or flight data resulted. Although not a serious problem, this does indicate the need for careful testing and documentation of all system parameters during preflight checkout, including monitoring of all interface signals to detect such anomalous pulses.

A high supply current condition was experienced on the data system utilized on experiment S0014 during initial turn-on at the experimenter's facility, preventing EPDS testing. The problem had been encountered before, during preflight testing, and occurred again at the manufacturer's laboratory. However, no fault was found and the unit subsequently performed normally. This type of behavior is typical of the latchup phenomenon, but the actual cause has not identified. Additional system level tests are planned.

POST-DEINTEGRATION FINDINGS: EPDS

- M0003: 1 of 2 EPDS was thought to have failed: appeared to be locked into continuous data record mode
 - Flight data apparently not affected
 - Failure analysis showed problem was related to GSE, there were no flight hardware failures
- M0004: High standby current traced to early turn-on of experiment, not a failure
 - Relay chatter due to GSE timing
- S0014: Not yet tested (Gulsten data system problem: high current)
 - Complete system test planned

POST-DEINTEGRATION FINDINGS: EPDS (CONTINUED)

Several other anomalies involving experimenter electronics remain to be analyzed. Some are apparently recurrences of problems which were noted during preflight testing (e.g. the Gulten data system). In addition, some systems have not yet completed their post-flight test programs. Following this operational test phase, the present plan is to test all EPDS units for parametric shifts, and to perform an internal inspection, to determine if any changes related to the LDEF flight occurred.

POST-DEINTEGRATION FINDINGS: EPDS

- S1001: System test planned
- S1005: Limited system test: normal
 - Complete thermal-vacuum testing planned
- A0201: Test plan not yet finalized

Present plans are to test all EPDS at Boeing for changes in sensitive parameters, and inspect for changes related to LDEF experience

MAGNET TAPE MODULE (MTM)

Seven two-track MTM's were supplied by NASA as part of the EPDS units. A single four-track MTM was also utilized on another experiment. Flight data was recovered from all units. However, the four-track unit failed to switch to the second set of tracks after completion of its first set, resulting in overwriting some of the early data. Failure analysis will be performed.

All other units functioned normally, with only minor anomalies noted. However, two effects of long term storage of the magnetic tape were noted. On those units which sat for an extended period without being operated after completion of their programmed mission, the tape took a "set" where it wrapped around the non-metallic capstan (but not elsewhere). In addition, it was noted that similar tape stored in dry nitrogen on earth exhibited a loss of adhesion of the magnetic oxide material. Dry nitrogen storage is not a preventive for material degradation. Fortunately, this did not occur in the flight units, which had some internal humidity or other gaseous contamination.

These findings will be investigated by the MTM or tape manufacturer, respectively and should be of value in planning future long term missions.

Magnetic Tape Systems (MTM)

- Data recovered from all recorders
- Relay failure on 4-track MTM
- Tape took "set" around non-metallic capstan in six of seven 2-track recorders. Exception was the only unit which operated periodically throughout the mission
- A0180 tape stored in dry nitrogen on ground exhibited loss of oxide adhesion on replay. Similar tape in sealed flight unit did not show adhesion loss
- Capstan motor brush or bearing noise on one unit
- All electromechanical systems functions were nominal in post-flight bench tests

WIRE HARNESSING: COMPONENTS AND CONSTRUCTION

The LDEF wire harness consisted of the cabling between the EIS box and all 24 active experiments, some inter-experiment cabling, battery cabling, and thermocouple wiring. It was assembled in-place in the LDEF structure, with extensive use of Nylon cable ties and harness clamps. At KSC, it was inspected in-place prior to any disruption other than disconnection of experiments. After removal of the experiments, electrical continuity and 500 volt DC insulation resistance tests were performed on the harness. It was then removed intact, and several EIS harness assemblies were removed for further detailed inspections and tests at Boeing. Construction and components were typical of current practice, except that some of the connectors did not receive a vacuum bakeout. No problems resulted from this condition.

Wire Harnessing: Components and Construction

- **Some connectors contained non-space rated polymeric materials (no vacuum bake)**
- **EIS cabling: Teflon jacketed, braided copper shielded cable comprised of 7, 20 gauge, teflon insulated, copper conductors**
- **Cable harness clamps and cable ties: Nylon**

TYPICAL WIRE HARNESS INSTALLATION

Special clamps were fabricated to provide attachment points on the LDEF frame without drilling holes into structural members. The harness made numerous bends over structural members, with extensive use of clamps and Teflon jacketing for protection.



TESTING PERFORMED

Electrical and mechanical tests were performed to detect any deterioration or breakdown. When appropriate, these were performed while the harness was still in place in LDEF, prior to any movement which might have disturbed or corrected shorting conditions.

WIRE HARNESSING TESTING PERFORMED

- **Electrical testing**
 - **DC resistance**
 - **Insulation resistance**
 - **Dielectric withstand voltage**
 - **Contact resistance of the crimped contact wire junction**
- **Mechanical testing (connectors)**
 - **Contact insertion and removal forces**
 - **Socket engagement and separation forces**

TEST RESULTS

The entire wire harness performed flawlessly. No deterioration of any components or degradation of electrical properties was observed. It should be noted that the wire harness was not directly exposed to the external environment (notably atomic oxygen), being protected by the experiment trays (metal) and the LDEF frame structure.

Exposed wiring on some experiments was subject to some deterioration of the exterior sheath materials. The results of this exposure will be documented by the System SIG.

A copy of the wire harness test report is available on request.

WIRE HARNESS TEST RESULTS

- Visual examination: no deterioration of wire harness components
- Electrical testing: no degradation of the electrical properties of the cabling
- Mechanical evaluation: reveals all components intact and fully functional

A0038 - INTERSTELLAR GAS EXPERIMENT (IGE)

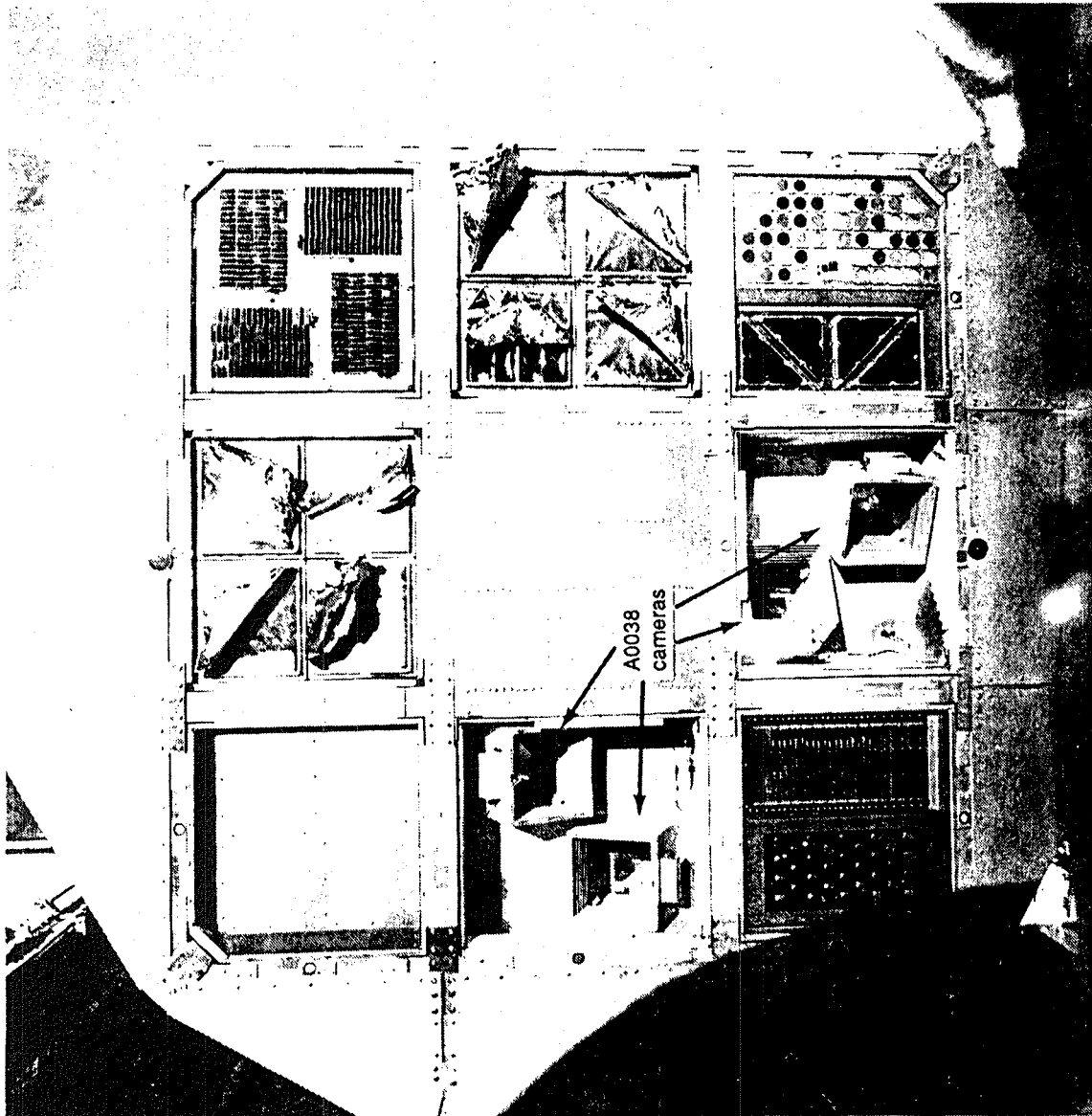
A0038 was one of the most complex experiments on LDEF; it also experienced the only major electronic systems failure. Seven "cameras" each containing five copper-beryllium foils, were to collect gas atoms. The foils were to be sequentially rotated out of their exposed position by firing pyrotechnic "squibs" when pulsed by their electronic sequencer units. It was found that only one of the 35 foils had rotated during flight. The experiment also used "E-cell" micro-coulombmeter units to record the length of time high voltage had been applied to the camera grids. A number of these E-cells apparently leaked, destroying their sockets with the corrosive internal electrolyte. Failure analysis of the electronic systems is being conducted at Boeing, and preliminary findings are presented on the following pages.

A0038 - INTERSTELLAR GAS EXPERIMENT

- Objective: collect interstellar gas atoms in Cu-Be foils
- Four trays with total of seven "cameras". Each camera contained five foils designed to rotate from horizontal to vertical in programmed sequence. 1200 volt ion suppression grids.
- Sequencer pulses pyrotechnic, cuts wire causing foil to rotate
- Only one of the 35 foils rotated
- Severe contamination on exterior surfaces
- Several E-cells (coulombmeters) leaked:
 - sockets destroyed
- Failure analysis being performed at Boeing

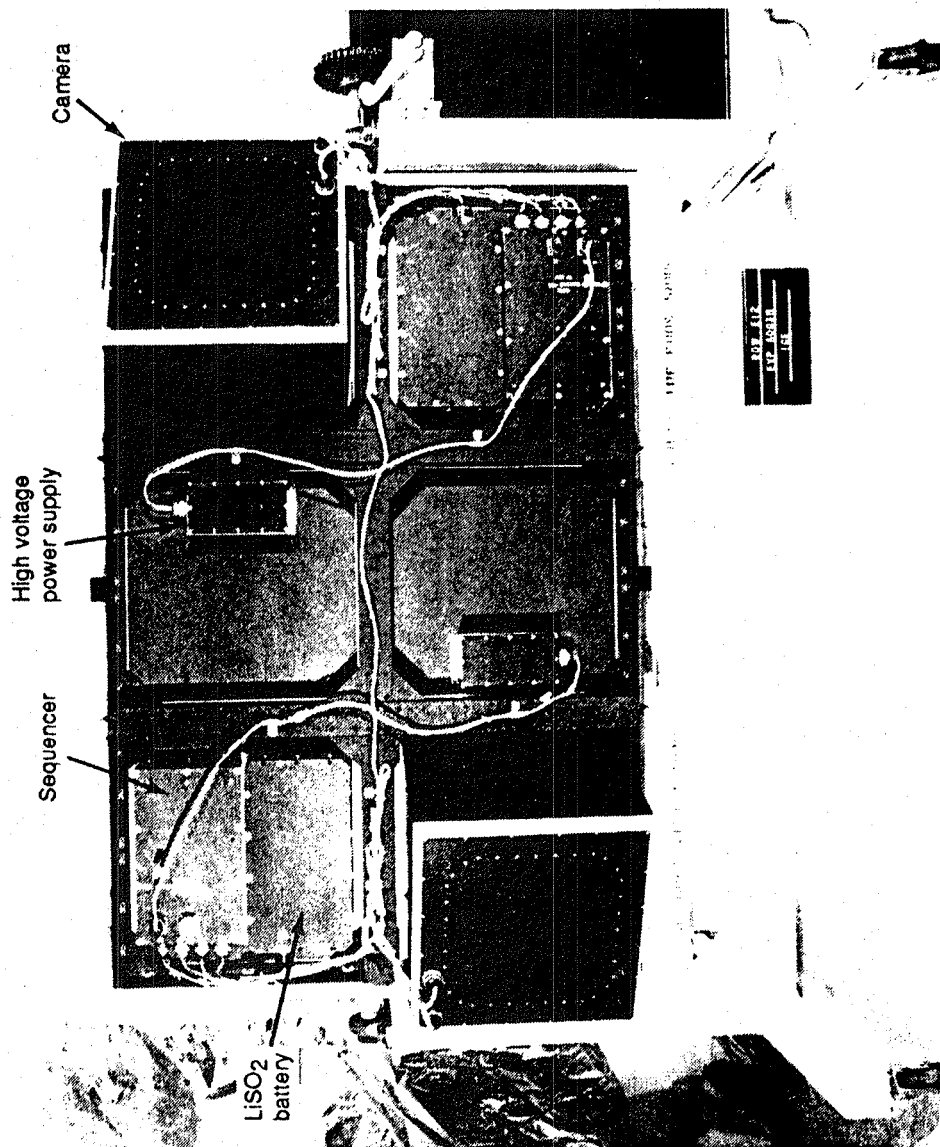
SPACE END OF LDEF, WITH TWO IGE TRAYS PLUS OTHERS

This in-orbit photo shows two of the four IGE trays, each containing two cameras. The IGE cameras (angled box enclosures) contained the flat foil plates, each hinged along one bottom edge and intended to rotate toward the front of the camera box, stopping when parallel to the box sides and out of the direct path of gas atoms traveling through the camera to the next foil in the sequence.



REAR OF ONE OF THE IGE TRAYS

Shown are the batteries and sequencers (diagonal corners), and the backs of two cameras with associated high voltage power supplies.



A0038 - FAILURE ANALYSIS OBSERVATIONS

The experiment systems were activated by the EIS system, which operated a single master initiate relay. This was found to be activated ("set"), and six of the seven slave relays (activated from the master relay) were set. One slave relay did not activate during flight and its sequencer (tray F6) was never turned on. Intermittent operation of the F6 slave relay has been confirmed. The remaining six sequencers had been activated in flight, but only one of the squibs fired.

A0038 - FAILURE ANALYSIS OBSERVATIONS

- EIS activated master relay which was to activate slave relays in the seven sequencers
- Six of seven sequencers activated but only one of 35 pyros fired
- Seventh sequencer (tray F6) never activated in flight. Relay worked in post-flight testing at KSC, failed once in lab
 - Problem with drive circuit, connector, or relay?

A0038 - FAILURE ANALYSIS OBSERVATIONS (CONTINUED)

There was an LDEF requirement that electronic systems be isolated electrically from the LDEF structure. However, at least two experiments (including IGE) were evidently designed to use the LDEF as a ground reference. The IGE electronics were indeed isolated from the tray structure, but the various chassis boxes and the camera box structure were bolted directly to the tray. This made the tray the ground reference point for one of the camera internal grids. Neither electrical terminal of the high voltage power supply was connected to the tray, resulting in uncertainty as to the actual voltage between the camera grids and the camera body. Also, in a late pre-flight change for thermal control purposes, the sequencer chassis were isolated from the trays by insulating washers.

Despite the grounding confusion, all electrical systems had ground return leads in their cabling, which completed the circuits and allowed them to function. Testing at Boeing confirmed that all sequencers and high voltage supplies functioned normally, using flight cables and accelerated clock timing. Confirming activation of the trays, all batteries except that of the tray with the faulty initiate relay (F6) were fully discharged, as expected.

A0038 - FAILURE ANALYSIS OBSERVATIONS

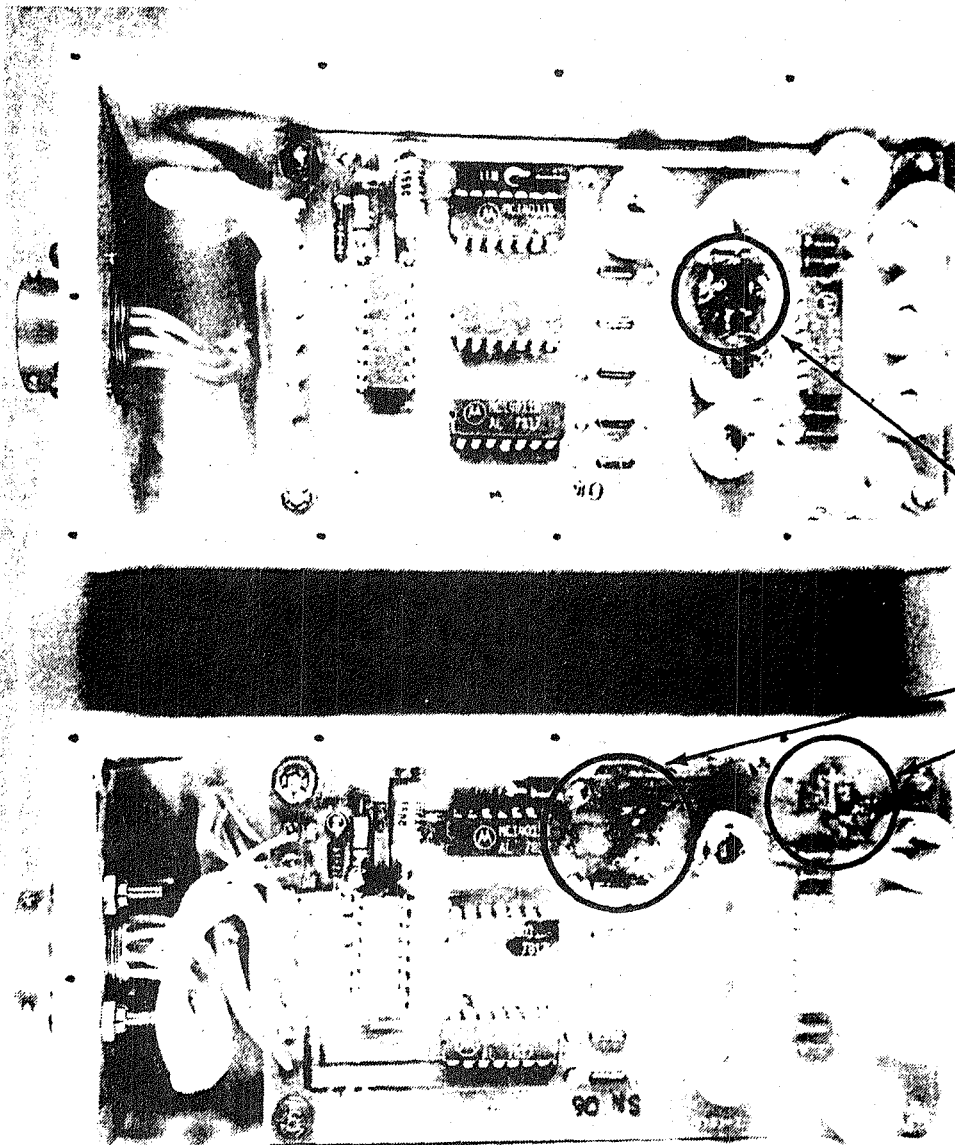
- E-cells record integrated currents
 - some apparently leaked, destroying sockets
- Electronics isolated electrically from chassis and trays
- All sequencers and HV supplies pass functional tests
 - fired pyro simulators (flash cubes)
 - timing sequences correct
 - all batteries (except F6) discharged (HV turned on)
 - F6's battery at 70% of capacity

PHOTOGRAPH OF THE EFFECTS OF E-CELL LEAKAGE

This photograph shows the interior of two of the four high voltage power supplies (HVPS) that contained failed E-cells (the photograph was taken after the E-cells had been removed). Each of the seven HVPS used on A0038 contained ten E-cells. A total of five of the seventy E-cells showed signs of electrolyte (phosphoric acid) leakage. The disintegration of the sockets was apparently caused by the electrolyte leakage.

Four of the seven HVPS were mounted on the exterior surfaces of the experiment while the remaining three were mounted on interior (inside of LDEF) surfaces. All four exterior HVPS experienced at least one E-cell failure while the interior mounted HVPS possessed no failed E-cells. This leads us to believe that operating temperatures played an important role in the E-cell leakages.

The leakages did not seem to effect the overall performance of the individual HVPS, but further testing is required to confirm this.



E-cell sockets destroyed
by leaking E-cells

A0038 - FAILURE ANALYSIS PLANS

This analysis is still in progress. A number of unanswered questions remain, given that the electronic sequencers operate normally in the laboratory. Testing of control and flight squibs, including the two squib that did fire, is underway at the JSC Pyrotechnic Test Lab. Non-destructive testing will include; photography, weights, resistance, X-rays at two angles, and N-rays at two angles. Destructive testing will be performed if required. If the squibs appear to operate normally, additional testing of the electronic systems, including a reassembled tray and real time testing may be required. These may include examination of possible noise effects on the internal clocks (e.g. inadvertent reset operations).

The effect of the floating high voltage ground needs study to assist in interpreting the results on those foils which were exposed during flight. In addition, it is desirable to complete the failure analyses on the E-cells and relay, to determine conclusively whether these anomalies were results of the LDEF orbit exposure.

A0038 - FAILURE ANALYSIS PLANS

- Why did pyros not fire?
 - Inspect and test flight and control hardware
 - Joint effort with JSC
- Why did E-cells leak?
- How long were HV supplies on?
 - Battery usage vs actual current drains
 - Read E-cells
- Why did F6 relay fail?
- What was the effect of floating ground?

A0187-1 CHEMISTRY OF MICROMETEORIDS

The experiment utilized sets of foil collector plates hinged along one side and controlled to open or close in a clam shell fashion. They were launched in the closed position. During flight they were to open for 300 days, and then close. On recovery they were found to be open. Preliminary analysis shows there was no stop designed into the timer sequence, since the original LDEF mission was to have only lasted 18 months. It appears that there was sufficient battery life to operate the clamshells more than once, and they happened to be open at the time of recovery due to the programmed open-close time periods. Failure analysis will be performed to verify the results of this preliminary analysis.

A0187-1 CHEMISTRY OF MICROMETEROIDS

- Objective: obtain chemical analysis of meteoroids
- Two sets of clam shells launched in closed position, programmed to open after 10 days and then close again prior to retrieval
- LDEF retrieved with clam shells in open position
- Had to bypass sequencer to electrically close clamshells at KSC and JSC - why?
- Sequencer at Boeing for failure analysis
- Analysis of schematic shows no stop in sequencer: clam shells kept cycling (308 days open, 212 days closed)
- Failure analysis to verify failure mode

A0187-1 TRAY IN ORBIT, WITH CLAMSHELLS OPEN

The two rows of four foils are each hinged along their longitudinal axis, and would have folded together prior to recovery if the intended sequence had been followed.



FOLLOW-ON ACTIVITIES

This tentative listing of planned activities is subject to change. It is presented to suggest the types of studies which are needed to determine whether any orbit-related changes in hardware took place. These include completion of failure analyses on all reported failures, and detailed parametric measurements on those systems for which adequate preflight documentation exists. It is possible that significant changes may have occurred in certain components without causing a functional failure. Any such changes would be of considerable interest and potential value in predicting usable lifetimes of similar electronic systems.

It was recognized early in the LDEF program that many systems would not utilize fully space qualified components, due to the low budget nature of the program and similar constraints on the individual experimenters. In spite of these limitations, most systems worked as planned. Many of the observed anomalies were related to design limitations rather than component failures. This raises the fundamental question: To what extent is it necessary to utilize Class S or equivalent components, with their considerable cost penalty?

FOLLOW-ON ACTIVITIES

- Failure Analysis (FA):
 - Completion of two experiment systems (A0038, A0187-1)
- EPDS:
 - Inspection and testing: look for any indication of changes related to LDEF
 - Possible detailed component studies if changes are detected
- Evaluation:
 - Compare results obtained with unscreened components (mostly MIL-STD 883, Class B) with normal NASA requirements
- Monitor testing of PI hardware

PRELIMINARY CONCLUSIONS

Although shielding from extended exposure to atomic oxygen and other environmental effects is important, no failures occurred which indicate any new, fundamental limitations to extended mission lifetimes. The key requirement (in addition to following good design practices) seems to be the system test plan. Testing of components at temperature, voltage and timing limits, and extensive testing of systems (including thermal-vacuum and noise tolerance testing) is essential. This must include thorough documentation, particularly of the interfaces between systems, and special efforts to detect unanticipated noise or spurious signals which can affect system timing or operation.

Extensive outgassing and atomic oxygen effects were observed on many experiments and on the LDEF structure. Use of metallized Teflon and other films resulted in quantities of loose, conductive material which could cause problems in some systems. This area requires considerably more investigation, including long term degradation studies and controls on allowable materials for long mission lifetimes.

PRELIMINARY CONCLUSIONS

- Most systems worked: relatively few failures occurred
 - LEO conditions permit long term use if systems are properly designed, manufactured, tested, and shielded
- Material outgassing and drifting, conductive materials are a potential hazard: exposed sensors, HV terminals vulnerable
 - Additional controls on allowable materials, and enclosures to capture (or exclude) loose materials may be required
 - Emphasize contamination control

PRELIMINARY CONCLUSIONS (CONTINUED)

Relays are a continuing problem area, well known in many production situations. Efforts have been made in some programs to eliminate them entirely, substituting solid state switches or other design approaches. There does not seem to be any magic answer. Typical approaches to minimizing these problems are listed.

The question of when to permit use of commercial or MIL-STD parts in space applications is complex, involving many concerns and tradeoffs. However, it is evident that such components can survive in some (perhaps many) space missions. It seems likely that such useage may be permitted in non-mission critical applications if conservative design rules are followed and comprehensive system testing is conducted. Further study is suggested.

PRELIMINARY CONCLUSIONS

- Relays are a continuing problem area
 - Use qualified vendors
 - Individual part screening at limits of specified voltages, pulse widths, temperatures, vibration, etc.
 - Redundancy
 - Alternative switch types if feasible
- Some low cost components were used successfully
 - May be possible to relax some rules under benign conditions, if proper testing, backup systems, and shields provided (thermal, radiation, atomic oxygen)
 - Additional study required

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Mechanical

Dr. Steve Spear

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OBJECTIVES

The primary objectives of the System SIG mechanical systems investigations are to determine the effects of long-term space exposure on (1) mechanisms employed both on LDEF or as part of individual experiments, (2) structural components and (3) fasteners. One of the most important objectives is to examine if space exposure will cause cold-welding problems with structural materials and fasteners to be used in assembled structures. This type of information is particularly important for successful Space Station Freedom (SSF) design. Specific components used on the SSF, such as orbital replacement units (ORUs), will require periodic replacement or repair. Any bonding or adhesion of the ORUs fastener assemblies will make on-orbit removal difficult.

MECHANICAL OBJECTIVES

Determine effects of long term space exposure on

- Mechanical systems and components
- Structural materials
- Fasteners

Mechanisms

- Evaluate functional performance
- Characterize condition of motors, bearings, lubricants seals, gaskets, etc.

Structures

- Areas of interest include erosion, wear, condition of welds, and microstructure changes

Fasteners

- Determine if relaxation, cold-welding or galling occurred
- Develop requirements for pre-flight installation practices to insure successful on-orbit or post-flight removal
- Does long term space exposure increase susceptibility to cold-welding?

**Mechanical Systems Hardware
of Interest Flown on LDEF**

Detailed lists of mechanical hardware flown on LDEF are available upon request.

MECHANICAL SYSTEMS HARDWARE OF INTEREST FLOWN ON LDEF

- Structures
 - Primary structure
 - 6061-T6 Aluminum
 - Ti and stainless steel components
 - Fasteners, trunnions, end support beam
- Mechanisms
 - Environment exposure control canisters (EECC)
 - Lubricants
 - Seals
 - Drive motor, drive screw, bearings
 - Circuit boards, electronics
 - Harnessing
 - Fasteners
- Motors
- Seals
- Valves
- Lubricants
- Instrumentation
- Miscellaneous
 - Including bearings, springs, gears, washers, cable cutters, pyrotechnics

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MECHANICAL HARDWARE EXAMINED TO DATE

- Fasteners
 - Tray clamp mounting bolts
 - Experiment mounting bolts
 - Intercostal fastener as-assembled
 - EECC canisters
 - Supported opening of all five canisters
 - End Support Beam spindle
 - Structural Materials
 - Metallurgical analysis
 - 6061-T6 aluminum primary structure
 - As represented by tray mounting clamps
 - Stainless steels
 - Tray mounting bolts
 - ESB spindle
 - Ti-6Al-4V intercostal clips
 - Cu grounding straps
 - Grapples
 - Viscous damper
- } Funded by JSC

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EECC

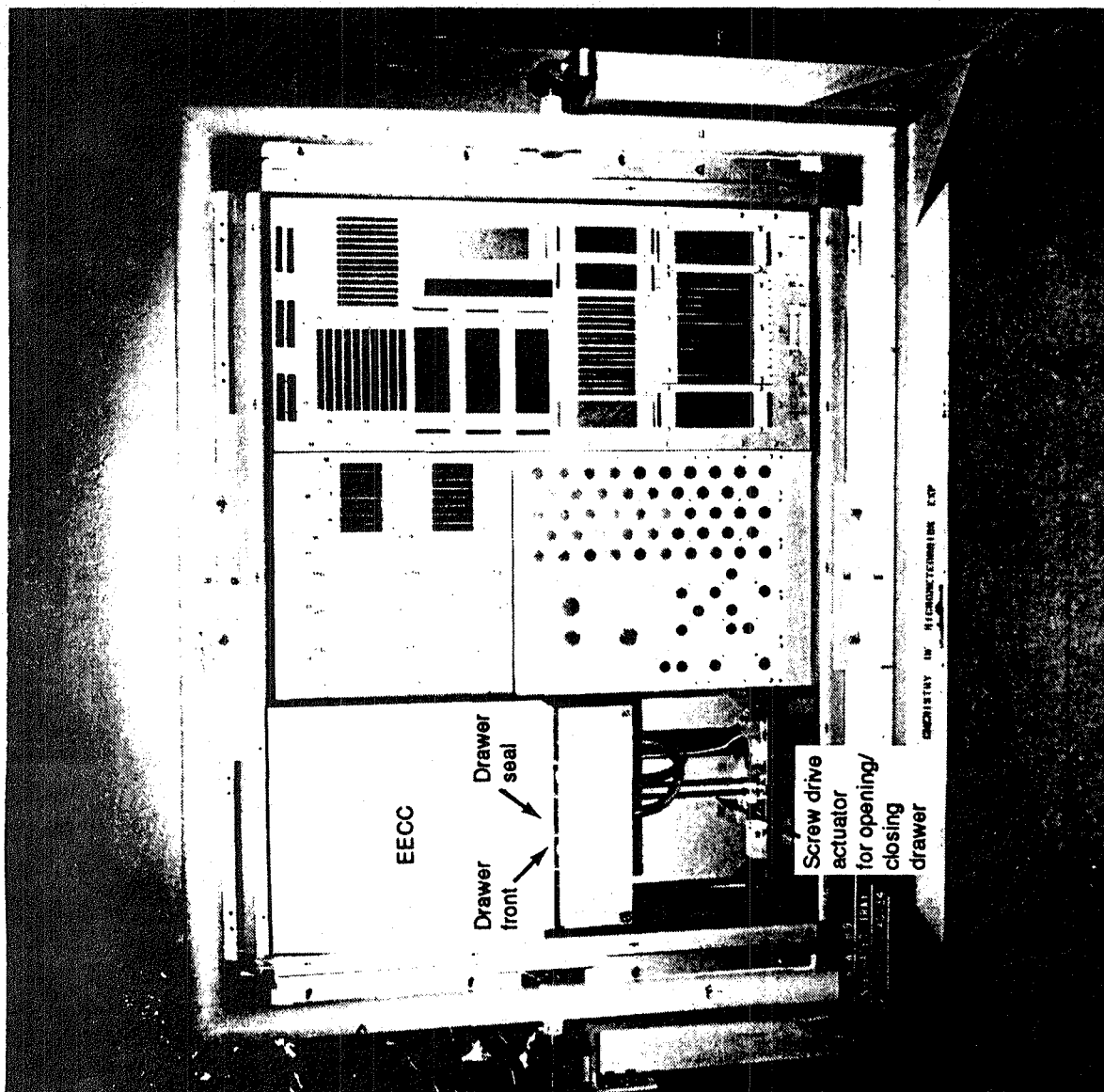
Dr. Steve Spear of Boeing and Dr. Dave Brinza of JPL assisted in the opening of all five EECC vacuum canisters flown on LDEF. This include on-site technical support in the openings of the Air Force (M0006), LaRC (S0010) and The Aerospace Corporation (M0003) canisters. Technical information to assist opening of the West German canister was provided. Information obtained of particular interest to System SIG objectives included canister pressures, leak rates, and drive motor currents during opening to evaluate effects of space exposure on the drawer actuation mechanism.

EECC

- Participated in opening M0006, S0010, M0003 canisters
- Provided technical support for opening of S1002 canisters
- In conjunction with Dr. Dave Brinza of JPL obtained:
 - Initial canister pressures
 - Leak rates
 - Internal gas samples
 - Drawer opening times
 - Drive motor currents

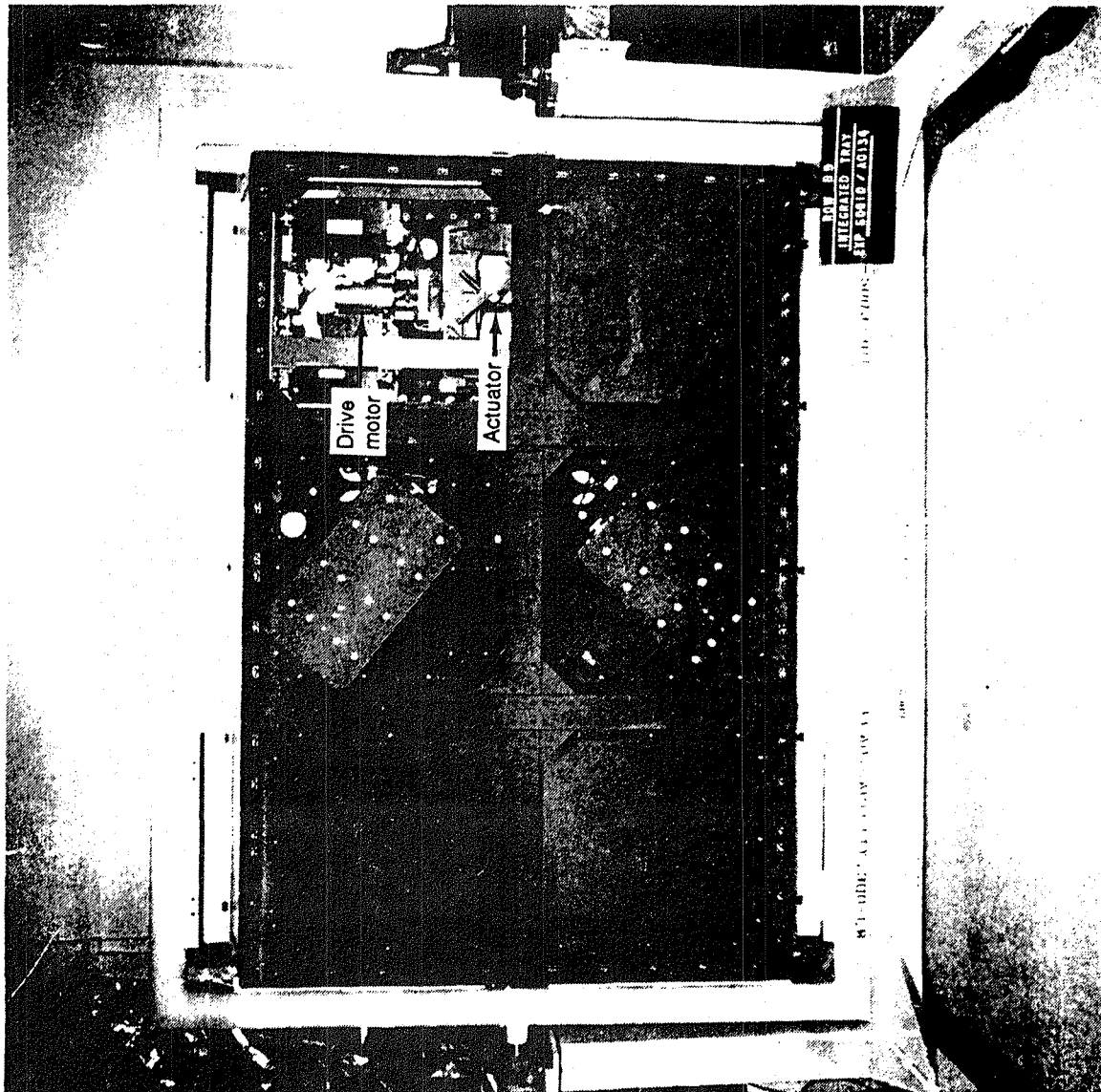
EECC

Photograph shows the EECC as mounted in an experiment tray. Drawer actuator is noted. Radiative heat shields cover the canister and drawer front to control the content's thermal exposure and protect the drawer sealing mechanisms.



EECC

Photograph shows backside of EECC as mounted in an experiment tray.
Drawer actuator and drive motor is noted.



EECC Performance Data

Data obtained during opening of the EECC vacuum canisters is shown. Due to GSE difficulties, the initial pressure data was not obtained for the M0006 canister. However, it was determined during the opening of the M0006 canister that a significant pressure differential existed. The S1002 experimenters stated that "we did not observe a pressure differential between the canister and ambient pressure" during the opening of their canister. The M0003 canister flown near the trailing edge of LDEF was holding a significant vacuum at the time of opening. The higher leak rates of drawer seals on canisters flown at or near the leading edge, in comparison to that of the M0006 canister flown on the trailing edge, are suggestive of the differences between AO exposure levels and corresponding damage to the seals. This effect will be investigated during testing of EECC hardware.

Typical drawer opening time was around 17 minutes. Motor currents oscillated between the limits shown during each revolution of the drive screw. The longer time to open the M0006 canister and higher than typical current draw are consistent with noise indications of higher torque loading of the motor noted during opening. Damage to the drive screw or its lubrication are possible causes to account for the degraded performance. The low motor current of the S0010 canister corresponded with observations of smooth and steady drawer opening. The S0010 canister was the prototype S/N 001 EECC. Its good performance is likely the result of "breaking in" of the mechanism during extensive operation during development testing.

Follow-on work on the EECC's will include investigation of the causes of the observed performance differences and relate them to the differences in space exposure conditions where applicable.

EECC Performance Data

Exp. No.	LDEF Location	Initial Pressure TORR	Leak Rate TORR/Day	Opening Time Minutes	Motor Run Current mA	Days EECC opened after LDEF at 1Atm
M0006 (Air Force)	C3 (Trailing)	<1 atm	2.7	19.5	130-230	60
S0010 (LaRC/SLEMP)	B9 (Leading)	642	12.3	16.9	110-120	100
S1002 (West German)	E3 (Trailing)	1 atm	--	--	--	129
M0003 (Aerospace) S/N 004	D8 (Off- Leading)	1 atm	12.6	17.0	150-180	140
M0003 (Aerospace) S/N 005	D4 (Off-Trailing)	282	-	15.4	150-190	150

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EECC STATUS

- Have received S1002 (West German) canister at Boeing
- LaRC S0010 canister to be shipped to Boeing
- Future activities to investigate space environments on seals, lubricants and mechanisms

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Metallurgical Analysis

Except for the titanium intercostal clips, all metals examined for microstructure changes were mounted on exterior surfaces of LDEF and, therefore, saw direct exposure to atomic oxygen and/or UV radiation.

The tray clamps were fabricated from the same aluminum alloy and temper used for the primary structure (6061-T6). Because of the availability and the variety of exposure seen by the various clamps, no structural members of LDEF were removed for evaluation.

Metallurgical Analysis

- **OBJECTIVE**
 - **Determine if space exposure causes microstructural and/or mechanical property changes of metals flown on LDEF**
- **METALS TO BE EXAMINED**
 - **6061-T6 aluminum tray clamps**
 - **Representative of LDEF primary structure**
 - **Ti-6Al-4V intercostal clips**
 - **Stainless steel tray clamp bolts**
 - **Copper grounding straps**

Metallurgical Analysis

The results of metallurgical analysis on aluminum, stainless steel and titanium components flown on LDEF has shown no microstructural changes caused by long term space exposure. The analysis of the copper straps used to ground the A0178 Ag/Teflon thermal control blankets is currently underway.

Metallurgical Analysis (Continued)

- **RESULTS TO DATE**
 - **Dye penetrant and eddy current inspection of primary structure at KSC indicated nominal condition**
 - **Metallographic sectioning reveals no microstructural changes in near-trailing and -leading edge aluminum tray clamps**
 - **Optical examination indicates no effects on Ti intercostal clips**

6061-T6 Aluminum Tray Clamp Cross-sections

Comparison of microstructures at exposed or protected (by shim) surfaces of the 6061-T6 aluminum tray clamps from near the leading edge (LEFT), and the trailing edge (RIGHT) illustrate that space exposure has no discernible effect on the bulk microstructures of typical structural metals. The microstructures are nominal. Mechanical property changes are unlikely in the absence of microstructural changes. However, surface analysis (including scanning electron microscopy) investigations of the anodized surfaces of the clamps, presented in the Thermal section showed some smoothing or erosion effects on exposed areas near the leading edge.

The microphotographs are cross-sections from two tray clamps. After standard metallographic preparation the specimens were etched to permit examination of microstructure undisturbed by the cross-sectioning procedure.

E10-6 (Near leading edge)

E2-6 (Near trailing edge)

Covered

Unexposed
top surface
of tray clamp

Exposed

Exposed
top surface
of tray clamp

0.002"

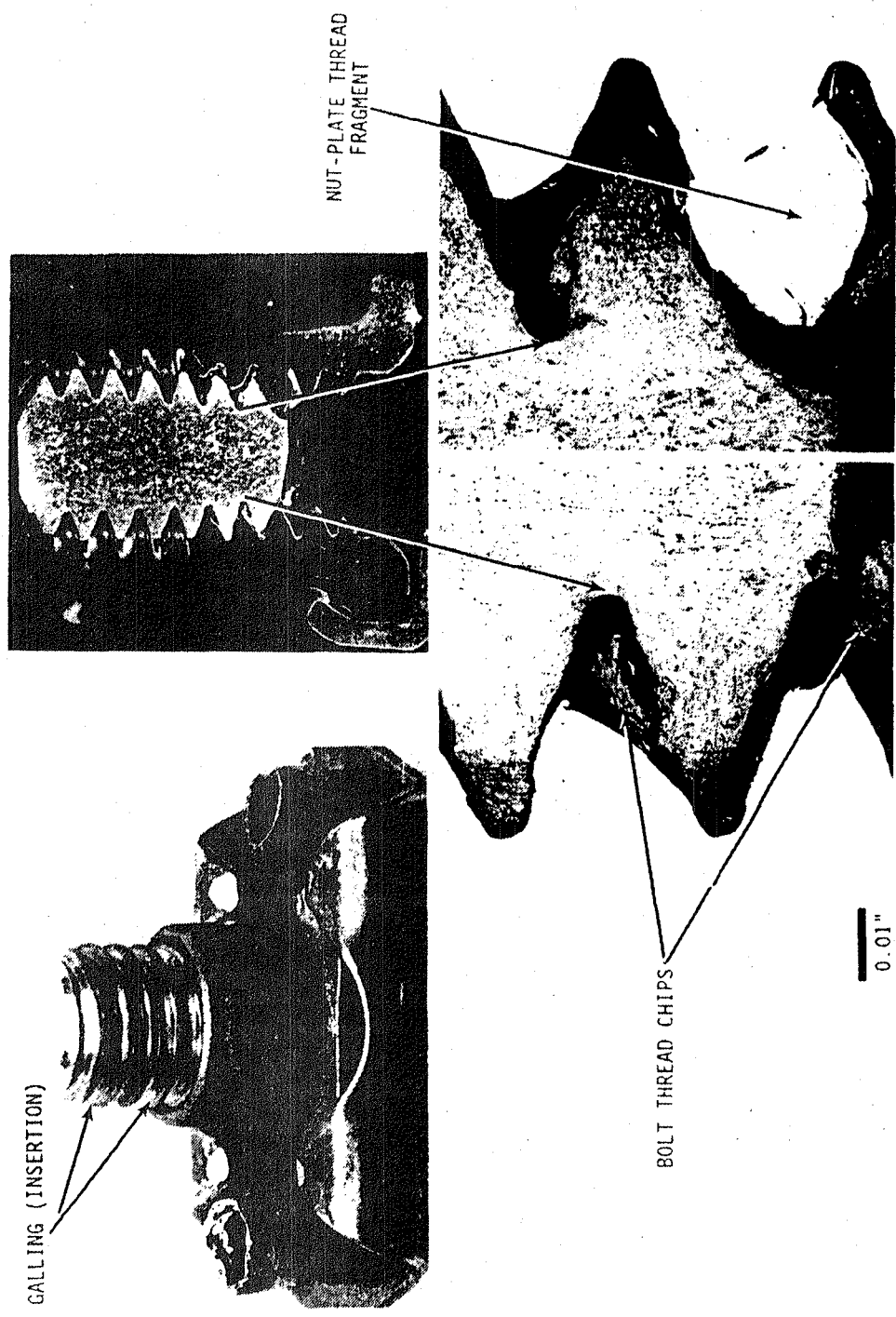
6061-T6 Aluminum Tray Clamp Cross - Sections
(Etched)

Mechanical Fastener Investigation

Observations of high removal torque values and extensive thread seizure or stripping problems were widespread for all of the various stainless steel fasteners flown on LDEF. The potential for cold-welding of fastener faying (mating) surfaces during long term space exposure is of particular concern in the design of removable or replaceable structures for spacecraft. Coldwelding can occur between atomically clean metal surfaces when carefully prepared in vacuum. However, from a design standpoint, we need to determine whether cold-welding will occur under on-orbit environments.

Visual examination of a large number of stainless steel bolts indicated that the problems were most likely related to installation damage. Metallographic sectioning of seized bolts confirmed this explanation. As an example, the facing figure shows that in the case of one tray fastener, seizure and subsequent shearing was caused by galling damage induced during original installation. The galling damage was clearly visible on the exposed portions of the bolt threads. This galling is more pronounced than what would be caused by being cycled through the self locking feature contained within the nut plate. The original galling damage caused bolt thread chips and nut-plate fragments to be generated when removal was attempted. The chips then caused jamming of the threads. No evidence exists of cold-welding between the bolt and nut thread surfaces.

We have received three fastener assemblies from PI hardware possessing sheared bolts caused by attempted removal. Using the procedure described in the above paragraph, it has been determined that all three failures were the result of galling caused by pre-flight assembly and/or post-flight removal.



Fastener Sheared During Attempted Removal

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DEFINITIONS

The definitions on the following page were developed to define the three different causes of metallic wear and adhesion discussed within this report; cold welding, galling, and fretting.

DEFINITIONS

COLD-WELDING (Micro-welding): Solid state metallic bonding between atoms on opposing surface layers of similar or dissimilar metals. Contamination free surfaces are required for bonding to occur. The presence of lubricants such as naturally occurring oxides, contaminants contained within the atmosphere or organic films will effectively prevent adhesion. These contaminants (lubricants) can be removed, pre-flight or on-orbit, by fastener installation or during sliding contact. If the surface contaminants are removed on-orbit, they will reform very slowly, if at all, in the vacuum of space. Cold-welding is also dependent on compressive stresses between mating surfaces, temperature, abrasion, and time. In extreme cases, contamination films on metal surfaces can be penetrated under high contact stresses, resulting in cold welding of asperity contacts (Ref. 5). The susceptibility to cold-welding between dissimilar metals is enhanced by like crystal structures and similar atom sizes.

GALLING: Wear condition whereby excessive friction between high spots (asperities) results in localized welding with subsequent spalling, metal tearout or metal transfer and further roughening of the rubbing surfaces of one or two mating parts.

FRETTING: Type of wear that occurs between tight-fitting surfaces subjected to cyclic relative motions of extremely small amplitude such as caused by vibration. Fine wear debris powders are generated.

NOTES: 1) The symptoms/results of seizure are the same independent of whether they were caused by galling or cold welding. In both cases, photo-micrographs of a cross section of the seized joint would show solid state metallic bonding between mating surfaces. The difference is that cold-welding is caused by contamination free surfaces coupled with compressive stresses leading to metal adhesion where as galling is caused by excessive friction (due to poor tolerances, insufficient or improper lubrication, improper material selection, etc.) between asperities resulting in metal adhesion. Frictional heating during galling will enhance the metallic adhesion.

2) Cold welding can occur between atomically clean metal surfaces when carefully prepared in a vacuum chamber on earth (Ref. 6). The question is whether cold welding will occur in on-orbit service conditions. While we have not found any evidence of cold-welding occurring on LDEF, it is important to remember that, 1) none of the experiments or hardware flown on LDEF were designed to have cold-welding take place, 2) our investigation is ongoing, and 3) there have been several on-orbit failures on earlier spacecraft in which cold-welding is a suspected cause of failure (Ref. 7).

Reference 5: Metals Handbook, 9th Edition, pg. 154.

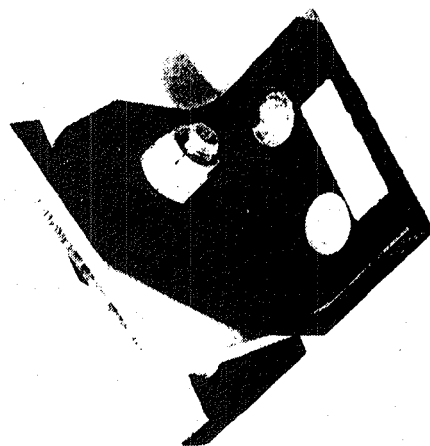
Reference 6: Hammel, R. L., "Propulsion Component Coldwelding Experiments Performed with an Earth Orbiting Satellite", TRW, 1969

Reference 7: Monroe, R. E., "Adhesion in the Space Environment", Battelle Institute, October 1966.

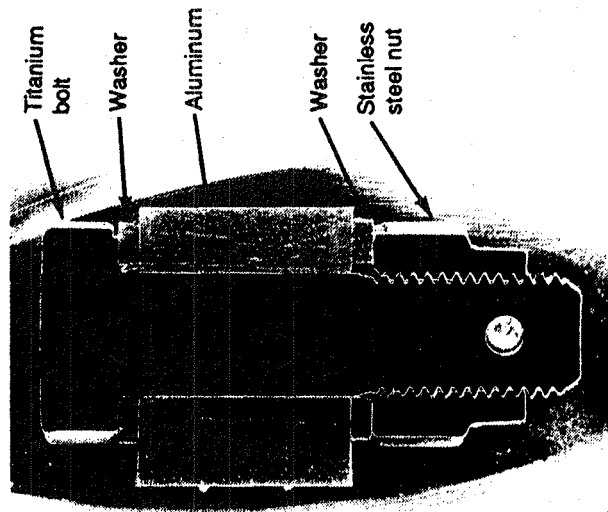
Unassembled Intercoastal Fastener

An unassembled, undisturbed, and as-flown titanium intercoastal fastener (LEFT) was cross-sectioned (RIGHT) to investigate the possibility of cold-welding without the complications of removal effects. The thread faying surfaces and bolt shank/aluminum plate interfaces were examined for indications of cold- (or micro-) welding. Close-ups of the areas of interest are shown in the following figures.

This fastener assembly was cross-sectioned because of its availability, not because we had evidence that cold welding had occurred.



Fastener Assembly



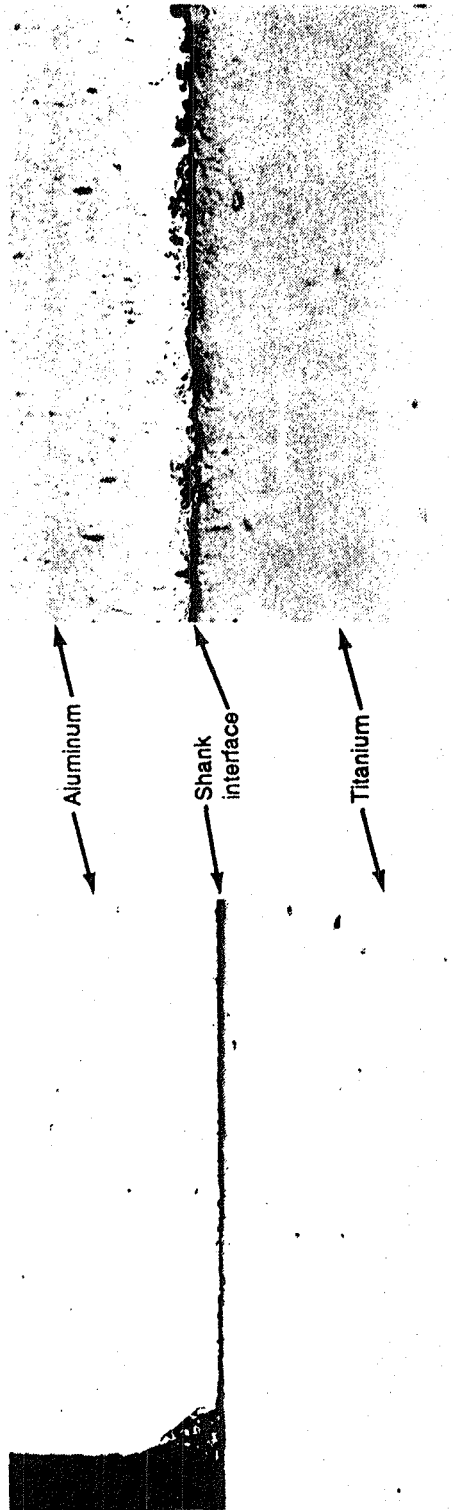
Cross-Section

0.040

Unassembled Intercoastal Fastener Assembly

Intercostal Fastener Cross-section

Examination of the bolt shank interfaces (opposite page) reveals no evidence of cold-welding. The thread faying surfaces (following page) also show no evidence of cold-welding; however, minor galling and some smearing of the silver-plating (specified for lubrication) on the stainless steel nut is evident.



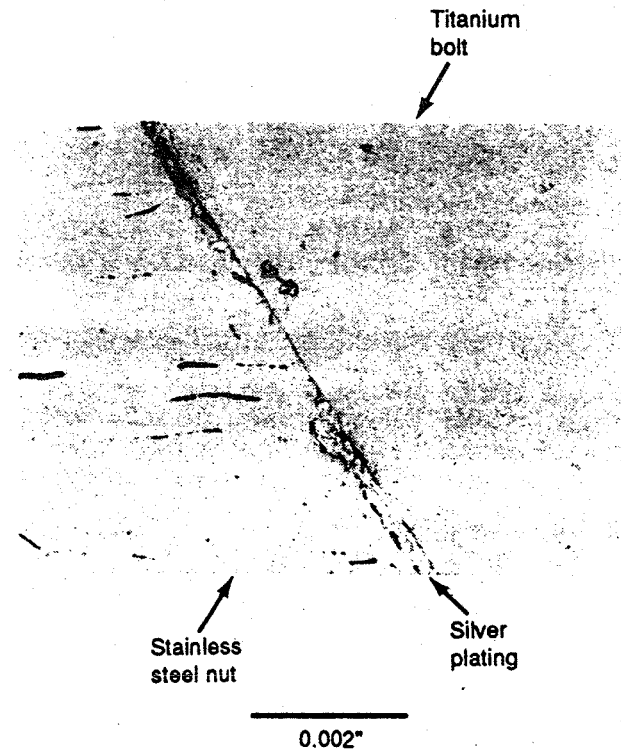
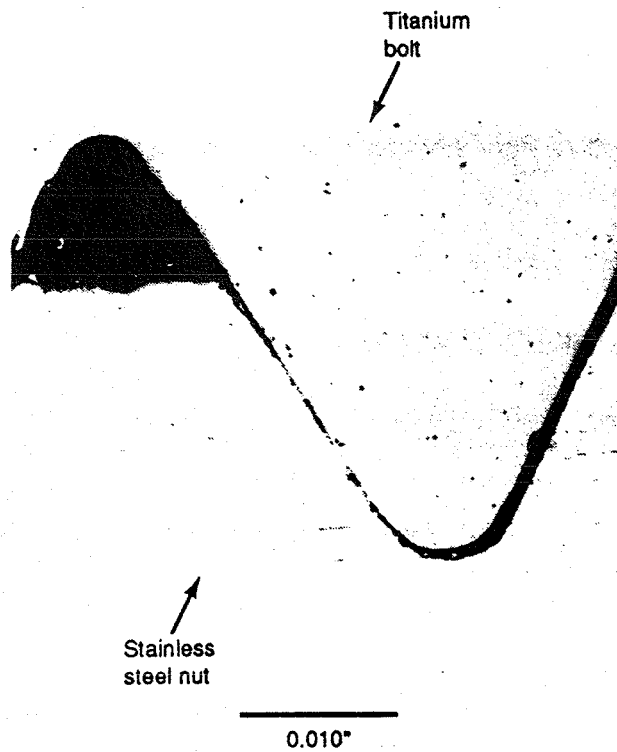
0.010"

0.002"

Intercostal Fastener Assembly
Cross-Section

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*Intercostal Fastener Assembly
Cross-Section*

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LDEF TRAY CLAMP FASTENERS

The tray clamp mounting bolts are 140,000 psi ultimate strength rated A286 corrosion resistant steel hex head parts with no finish. They were installed with alodined aluminum washers under the head and into self-locking helicoil inserts. The pre-flight installation torque was 75 in-lbs, plus or minus 5 in-lbs.

During deintegration of LDEF, all tray clamp fastener breakaway torques (unseating torques) were determined using a dial gauge torque wrench. In addition, running (prevailing) torques were determined for every third tray clamp bolt.

A database was created that contained all breakaway and running torques. The torques were then examined as a function of their location on LDEF. As can be seen on the following chart, the average breakaway torque values are similar throughout LDEF. This showed that there was no pronounced effect on fastener removal parameters by the various space environments. However, there was a large scatter in values. The database identified the bolts that were within the twenty highest and twenty lowest values. These bolts then underwent visual examination in an attempt to identify the causes of their high or low breakaway torques.

LDEF TRAY CLAMP FASTENERS

- 2,232 Tray Clamp Bolts
 - 1/4" - 20 x 0.75"
 - Self-locking helicoils on primary structure
 - Pre-flight torque was 75 in-lbs
 - 140,000 psi ultimate tensile strength, A286 stainless steel
 - Bolts alcohol cleaned, patted dry prior to installation
- 2,172 breakaway (unseating) torques in database
Results are as follows:
 - Space end, average of 252 bolts = 74 in-lbs
 - Earth end, average of 216 bolts = 73 in-lbs
 - Circumference, average of 1691 bolts = 71 in-lbs
 - Leading edge, average of 120 bolts = 78 in-lbs
 - Trailing edge, average of 144 bolts = 72 in-lbs
 - Average of twenty lowest values = 31 in-lbs
 - Average of twenty highest values = 175 in-lbs
 - Range of values, 205 in-lbs to 10 in-lbs

LDEF TRAY CLAMP FASTENERS (cont'd)

No correlation was found between the bolts that possessed high running torques and high breakaway torques. There was only one bolt that possessed both one of the twenty highest running and twenty highest breakaway torques.

LDEF TRAY CLAMP FASTENERS

- 716 Running (prevailing) torques in database. Results are as follows:
 - Average running torque = 17 in-lbs
 - Average of twenty highest = 58 in-lbs
 - Range of values, 132 in-lbs to 2 in-lbs
 - No correlation between high running and high breakaway torques
- Need to determine cause of high and low values

LDEF BOLT/WASHER DAMAGE RATING CODES

This chart shows the code that was developed to assist in the visual inspection of the fasteners. To date 54 bolts have been examined using this code. In addition to the bolts possessing extreme removal parameters, several "average" bolts have been examined for comparison purposes.

LDEF Bolt/Washer Damage Rating Codes

- **Bolts**

B1 = No galling, very little thread scoring

**B2 = Light galling/thread wear, no deposits,
thread crests may be sharpened or rounded**

**B3 = Medium galling, threads may be sharpened,
or rounded, few deposits and smears, few areas
of metal removal**

**B4 = Heavy galling, threads sharpened or rounded, several
deposits, smears, or areas of metal removal, slivers**

**B5 = Threads mostly removed, much smearing, deposits,
metal removal**

- **Washers**

W1 = Very little smearing or scoring

W2 = Moderate smearing or scoring

W3 = Heavy smearing or scoring

LDEF Tray Clamp Fastener Conclusions

Visual examination of several of these bolts and washers has revealed a variety of bolt thread conditions from threads that appear to be almost unused (only a very fine burnish-like line on the flank or flat of some threads) to such severe galling as to entirely remove several threads. Many bolts have what appears to be aluminum deposits on the unthreaded or grip part of the shank between the threads and the bolt head, as if there was a hole misalignment between the clamp and the structure.

Visual examination of the mating washers also revealed varying degrees of scoring, burnishing and galling on both sides due to relative motion between bolt thread condition, possible hole misalignment, or washer condition, with the bolt torque values recorded during removal of the tray clamps that could lead to any decision regarding the occurrence of cold welding.

Future activities include: 1) continued visual examination of bolts and washers and 2) cycle new unused bolts in new helicoils to develop baseline data.

LDEF Tray Clamp Fasteners Conclusions

- Database created, subjective rating code established
- To date, 54 bolts/washers visually examined at 8x minimum
- Visual examination reveals a variety of bolt thread conditions ranging from appearance of unused to complete removal of threads
- Many bolts show signs of misalignment between bolt hole in tray clamp and bolt hole in the structure
- Visual examination of mating washers reveal variety of scoring, burnishing, and galling
- To date, no significant correlation has been found between thread condition, washer condition, and removal torques
- No evidence of cold welding has been found

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LDEF PRIMARY STRUCTURE RE-TORQUING

- All fastener assemblies re-torqued to pre-flight values per procedure LDEF-SED-014. Values lower than pre-flight were documented
- Bolt diameters ranged from 1/4" to 7/8". Silver plated nuts
- 2928 fastener assemblies re-torqued
 - Only 4% of the assemblies had "relaxed"
 - Nut rotations, to achieve pre-flight values, ranged from 5 to 120 degrees
 - Mapping of relaxed assemblies in progress
- Breaking torques of selected relaxed and non-relaxed bolts determined
- Intact intercoastal fastener assembly cross-sectioned

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PI Test Results

The French flew an experiment titled "Microwelding of Various Metalling Materials". The materials that were tested included Al alloys, Cu alloys, Ti alloys and stainless steel. Selected combinations of materials were chromic or sulfuric anodized. Other combinations used MoS2 and Molykote Z lubricants. The specimens were loaded together by the use of disc springs. All hardware has been removed and no microwelding has been found. Most of the material combinations are representative of sliding electric contacts or mechanisms used to deploy solar panels. These material combinations were selected so that microwelding did not occur. The results, to date, verify the selections.

Extensive seizure difficulties encountered during stainless steel fastener removal of LDEF experiment A0175 are of interest because of the use of cetyl alcohol as a lubricant during installation. The alcohol would have subsequently evaporated possibly leaving contamination-free (though not necessarily oxide-free) fastener faying surfaces that may have been susceptible to cold-welding. Unassembled, undisturbed fastener assemblies are currently awaiting metallographic cross-sectioning and examination at Boeing.

The System SIG investigation has found no evidence, as yet, of cold-welding between metals flown on LDEF. The presence of normal surface oxides, lubricants or contaminants on normally processed metallic materials would likely preclude the occurrence of cold-welding during subsequent space exposure.

PI Test Results

- **A0138-10 - Microwelding of Various Metallic Materials**
 - **Testing materials under load**
 - **Al alloy, Cu alloy, Ti alloy, stainless steel**
 - **Selected components chromic or sulfuric anodized**
 - **MoS2 and Molykote Z used on selected components**
 - **To date, no microwelding found**
- **A0175 - Evaluation of Composites in Space**
 - **Extensive seizing problems during fastener removal**
 - **Used cetyl alcohol as pre-flight lubricant**
 - **The cetyl alcohol has probably "evaporated" leaving clean metal to metal interfaces**
 - **Untouched fastener assemblies to be evaluated for galling/cold welding**

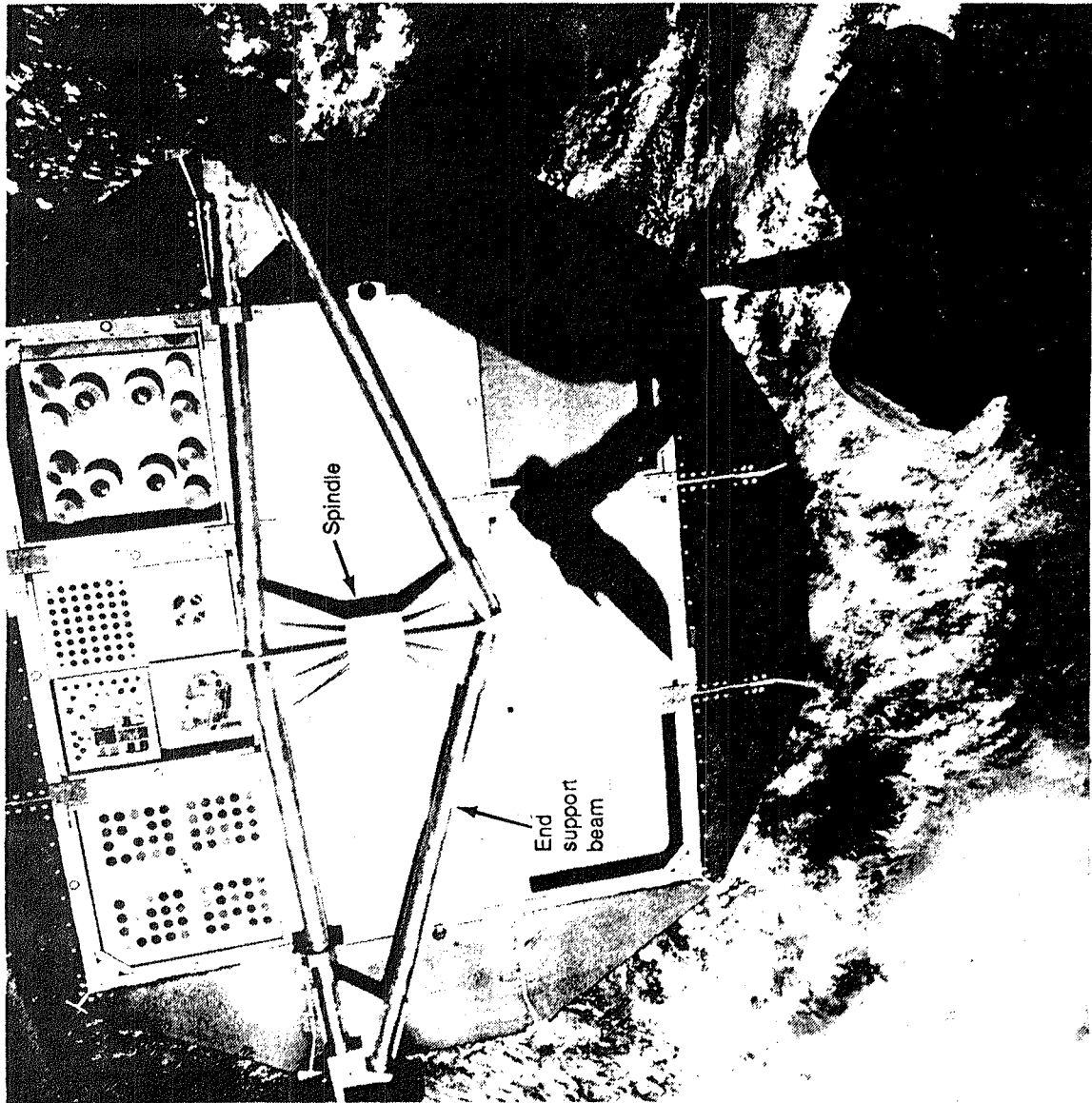
End Support Beam

The end support beam (ESB) was an 18 ft long aluminum frame that held the two end trunnions. It was designed to have a plus or minus 1.5 degree rotation about a 5" diameter stainless steel spindle to accommodate potential misalignment of the LDEF structure and still permit berthing in the shuttle cargo bay. A great deal of difficulty was encountered during removal of the ESB from its spindle (required for deintegration).

End Support Beam

- **$\pm 1\ 1/2$ degree rotation about spindle to accomodate potential misalignment of LDEF structure and allow berthing in shuttle cargo bay**
 - **Spindle: 17-4 PH stainless steel**
 - **ESB: Welded 6061-T6 Al Truss**
- **Removal of ESB necessary for de-integration**
 - **Difficulty encountered in removal**
 - **No problems noted pre-flight**
- **Analysis to determine cause of removal difficulty**

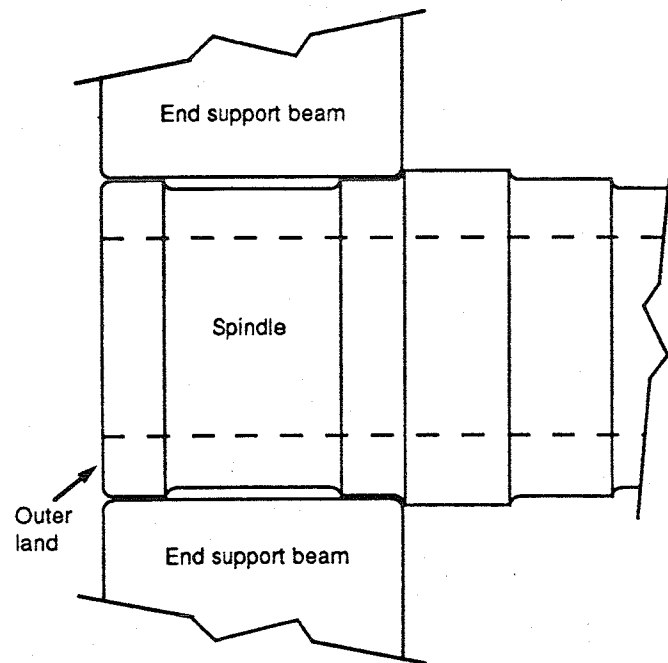
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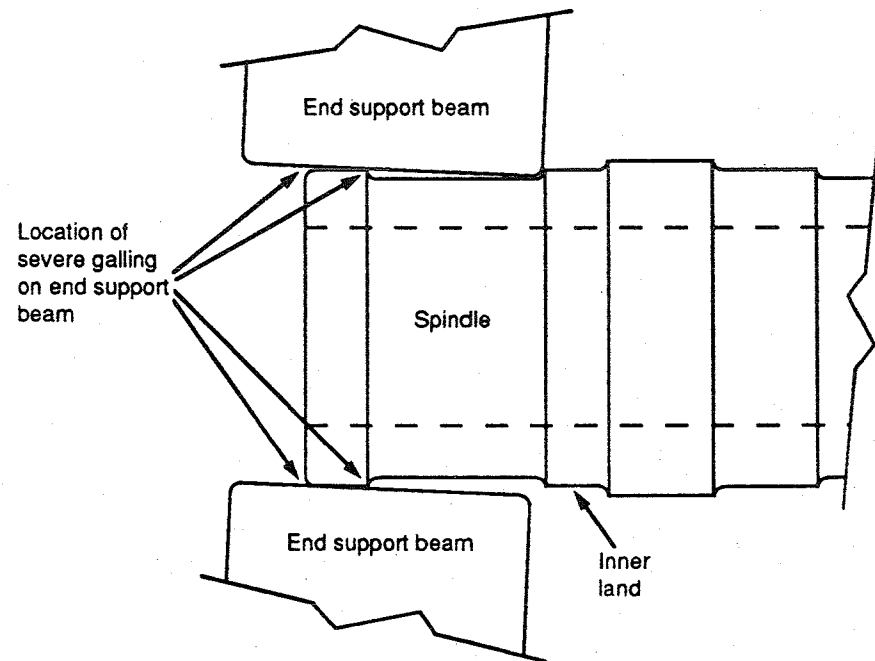
End Support Beam

During post-flight removal, no difficulties were encountered during the initial axial displacement of the ESB from the spindle. However, after approximately one inch of axial displacement had been accomplished, a great deal of difficulty was encountered.

Review of the video documenting the removal of the ESB strongly indicated these difficulties and the resulting galling damage to the aluminum ESB bore were caused by alignment difficulties. The hoist installed to support the beam apparently caused it to cock and jam on the spindle as the beam was pulled off of the first spindle land. Uncontrolled and excessive rotation of the jammed ESB about the spindle in an attempt to further move it caused extensive galling damage on the inner bore of the ESB as seen in the following photograph.



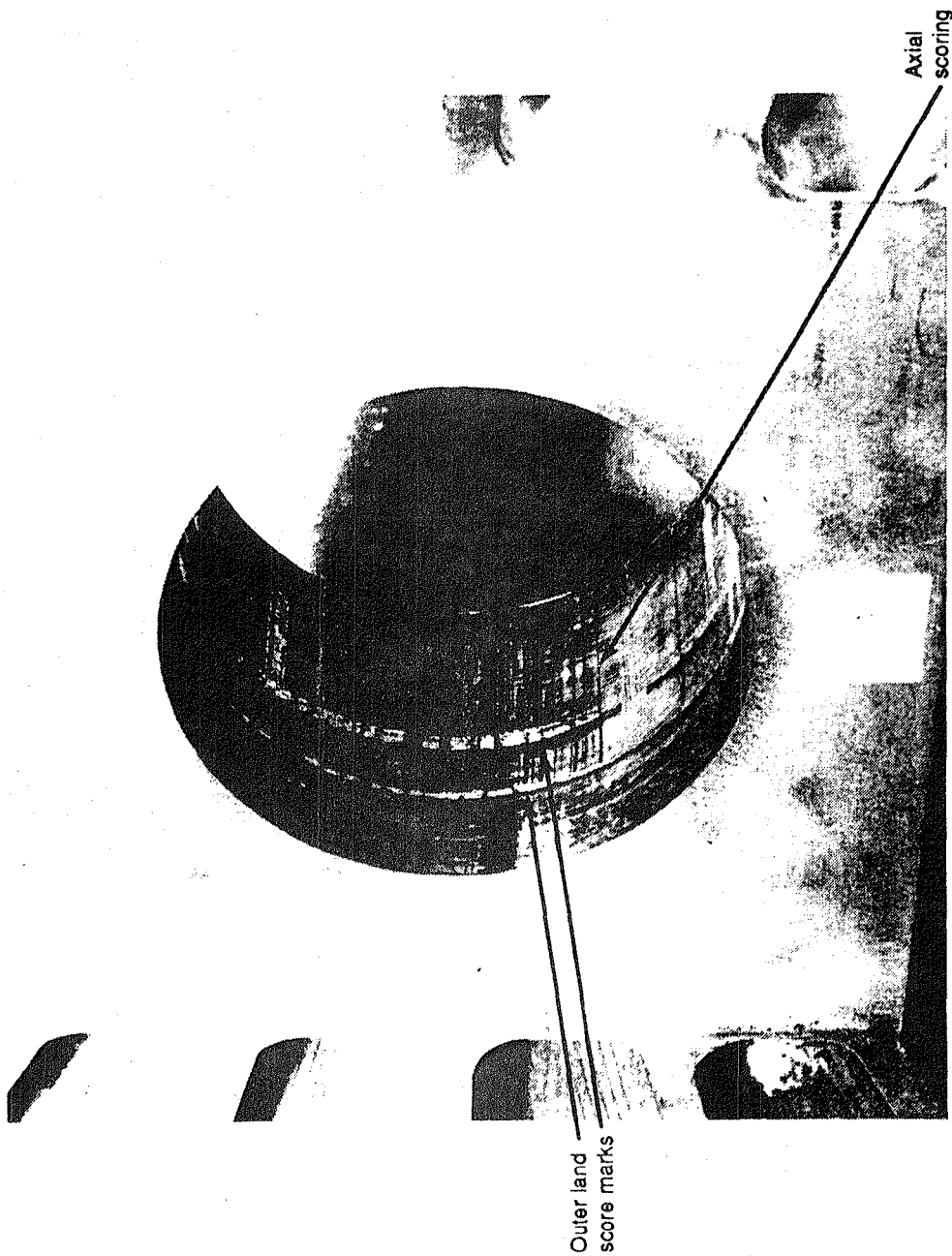
Flight Position of End Support Beam



Position of End Support Beam When It Became Stuck on Spindle During Removal Attempt

End Support Beam

Severe galling and scoring is apparent in the bore of the ESB. The two circumferential score marks nearest the front face of the ESB correspond to the position and width of outer land of the spindle when the beam jammed after coming off the inner spindle land. Uncontrolled rotation of the ESB about the spindle during further removal attempts caused galling between the stainless steel spindle and aluminum ESB which resulted in scoring of the softer aluminum. The axial scoring in the bore was caused when a gear-puller was finally employed to remove the beam.

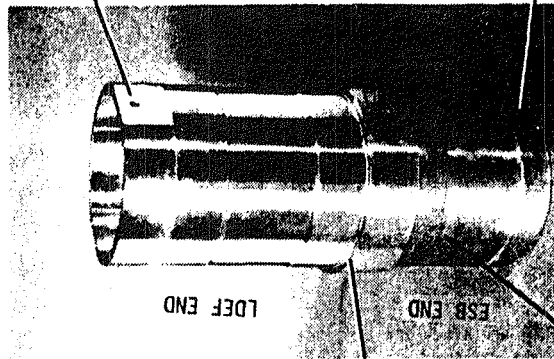
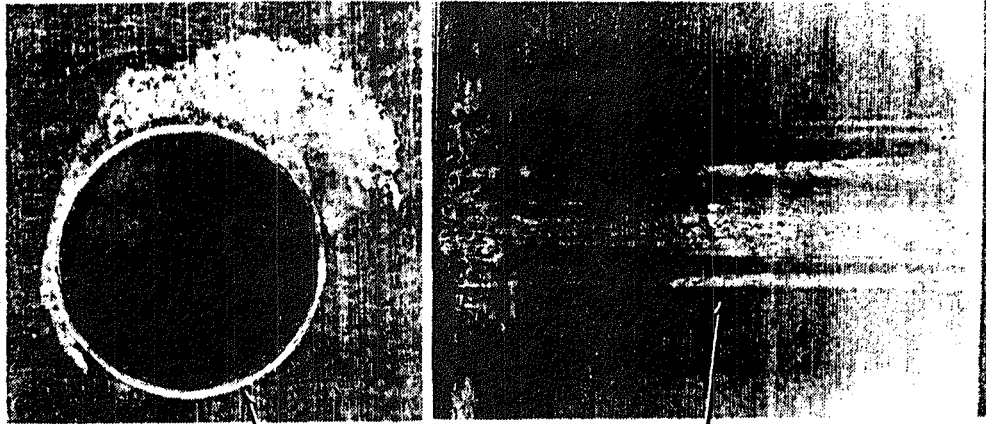


Front Surface of ESB
End Support Beam

ESB Spindle

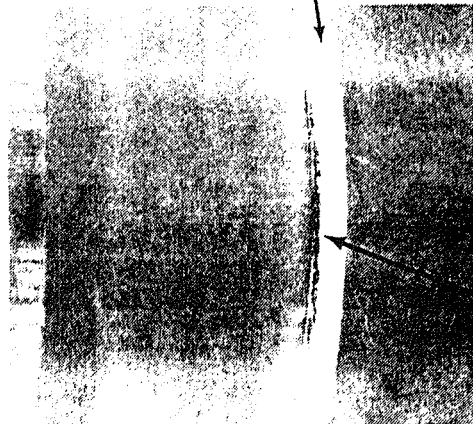
The lower right hand photograph shows galling damage/aluminum adhesion on the outer land of the stainless steel spindle. Aluminum was transferred to the edges of the land during rotation of the ESB. Subsequent gear-puller removal caused the axial streaks. Evidence of minor fretting damage was observed on the portion of the spindle inserted into the LDEF structure as indicated in the center photograph. Small relative motions between the LDEF structure and the spindle caused during transport and flight are the probable source of the fretting.

Metal transfer
associated with
galling



Galling and
aluminum
transfer

ESB Spindle

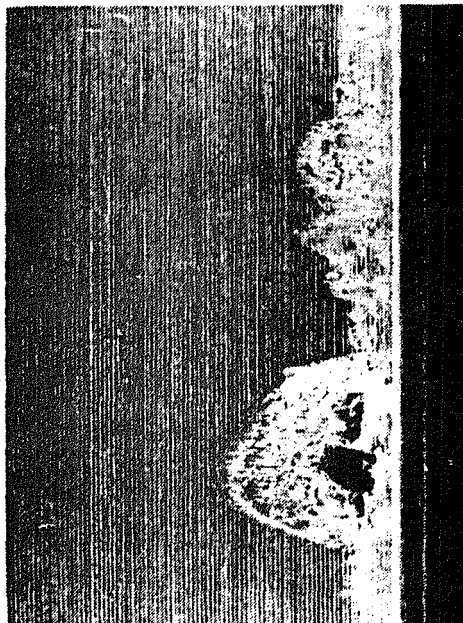


Fretting

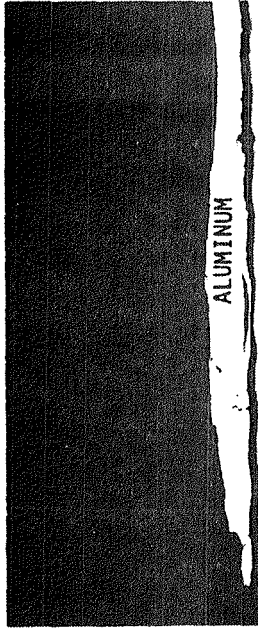
ESB Spindle

To confirm that the galling of the ESB bore and aluminum metal transfer to the outer spindle land was caused by removal damage and not cold-welding during flight, metallographic cross-sections were prepared. Shear deformations of the microstructure of aluminum stuck to the spindle land are consistent with removal motions. No evidence of cold-welding between the aluminum and the stainless steel spindle was observed.

The photograph on the right is a cross-section of the area shown on the left. As can be seen, there is no metal diffusion between the aluminum and stainless steel. The discrete interface between the aluminum and SS indicates that cold-welding did not occur.



GALLING AND
ALUMINUM ADHESION



SPINDLE

0.005"

ESB Spindle

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Grapple Fixtures

Both the rigidize sensing (active) and the flight standard (passive) grapple fixtures are undergoing post-flight evaluation to determine the effects of long term exposure to the LEO environment. This will provide critical information on the on-orbit performance of the grapple fixtures.

Grapple Fixtures

- **Two grapple fixtures**
 - **Rigidize sensing grapple designed to turn EIS on or off via RMS with LDEF still in cargo bay. Not used during retrieval since all experiments were inactive.**
 - **Flight standard grapple used to deploy and retrieve via the RMS on orbit**
- **Both grapple fixtures were returned to JSC for post flight examination and evaluation**
 - **Tungsten disulfide lubricant lifted from each grapple shaft for evaluation**
 - **CAM buffers removed for evaluation by materials and micrometeoroid study groups**
 - **Outer abutment plate removed for micrometeoroid evaluation**
 - **CAM action microswitches removed and sent to the manufacturer for testing**
 - **Trays removed for micrometeoroid and debris evaluation. Tray bolts and fasteners being evaluated by the McDonnell Douglas space systems Co.**
 - **Paint samples taken from each grapple fixture for evaluation**
- **Grapple fixtures shipped to Spar Aerospace (original equipment manufacturer)**
 - **Functional testing of the rigidize sensing grapple fixture to be performed**

Magnetically Anchored Viscous Damper

The viscous damper was used to provide attitude stabilization. The attitude of LDEF proved to be so stable that astronaut Brandenstein was able to fly the shuttle within the distance that allowed Bonnie Dunbar to merely extend the RMS to the grapple.

On-flight performance and post-flight test results prove the long term use of the viscous dampers on the Space Station, during segment attitude control, is a viable option.

A copy of the viscous damper test report is available upon request.

Magnetically Anchored Viscous Damper

- **Located on the centerline, in the body of LDEF, near the space end, to provide attitude stabilization from spinning, tumbling or oscillations, caused by deployment or other externally applied forces**
- **Post flight testing of the LDEF damper by the manufacturer, General Electric, Valley Forge, Pennsylvania, has been completed**
- **Test results show no anomalies**
- **Damper to be returned to Langley Research Center, in flight ready condition with 10,000 centistoke viscous fluid**
- **A purchase of 16 dampers is being considered for the use on space station during the construction phase**

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THERMAL CONTROL SURFACES EXPERIMENT (TSCE) - S0069

OBJECTIVE: To determine the post-flight operational condition of the TCSE flight hardware. Functional tests were performed and analyses conducted where necessary to determine the operational condition of the TCSE as a system. These functional tests included:

- Power-up transient monitoring of TCSE subsystems
- Functional test of both reflectance and daily measurements
- Analysis comparing the post-flight condition of the TSCE with the pre-flight condition

SUMMARY OF TEST RESULTS: The post-flight functional tests showed the system to be in surprisingly good health. Most subsystems and components are in good enough shape for the system to perform both reflectance and daily measurement functions. From tests and analysis of flight data, there are a number of anomalies that will require detailed analysis. These include:

- Failure of a relay in the flight recorder which resulted in loss of one third of the flight data
- Premature latch-up of the 25th clock bit
- Hanging of the carousel during rotation at sample 25 resulting in loss of some reflectance data
- Bad or excessively noisy data in some of the UV reflectance measurements both in-flight and in post-flight measurements

A copy of the ninety page "TCSE Post Flight System Functional Check-out Final Test Report" is available upon request.

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PRELIMINARY CONCLUSIONS

Difficult fastener removals related to galling during pre-flight installation and/or post-flight removal.

- Stainless steels are very susceptible to galling
- Successful application requires high thread quality and appropriate lubrication schemes

No evidence of cold-welding

End support beam removal difficulties caused by misalignment during removal

No metallurgical changes in aluminum or titanium

Dye penetrant and eddy current inspection of primary structure indicated nominal condition

All five EECC's opened successfully

- Cannister pressures and leak rates determined

The viscous damper and grapple post-flight test results are nominal

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Follow-On Activities

- **EECC's**
 - **Coordination of test plans with Aerospace Corp. and Wright-Patterson efforts**
 - **Analysis of component motors, gears, drive screws, lubrication, seals, bearings, springs, etc.**
- **Tray Clamp Fasteners**
 - **Continue visual examination of bolts and washers**
 - **Cycle new, unused bolts in new helicoils to develop baseline data**
 - **Sectioning of as-assembled flight and control joints**
- **Evaluation and analysis of additional experimental hardware and mechanisms such as:**
 - **A0187-1 micrometroid clamshells**
 - **Mechanisms, seals and lubricants**
- **Monitor PI testing of hardware**

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Optics

Tim Majoch

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OBJECTIVES

The objective of the System SIG Optics discipline is to develop a handbook and/or database that identifies hardware flown and results from testing of that hardware.

Unlike the Electrical and Mechanical discipline areas, the System SIG Optics effort relies primarily on the testing of hardware at the various experimenter's laboratories. This is because all optics hardware is part of individual experiments. Currently, we anticipate minimal testing of Optics hardware at Boeing.

A test matrix will be developed that contains hardware flown, the PI test plane, and tests desired by the Systems SIG.

Objectives

- **Optimize 'systems' investigations**
 - **Data provides useful information**
 - **Valid measure of effects of space exposure**
- **PI hardware is major source of information**
- **Develop test matrix of hardware flown, PI test plans, and tests desired by SSIG**
 - **Coordination of testing with PIs is critical**
 - **Further testing by SSIG identified laboratories**
- **Handbook/database w/results of systems investigations**
- **Results influence future design and use of space systems**

OPTICAL HARDWARE OF INTEREST

Optical hardware of interest falls into several categories. The following foils give the specific hardware breakdown within each category.

Glasses and filters are the first two types of hardware. Design ranges for these cover the ultraviolet through mid infrared ranges of the spectrum. Numerous UV and IR windows, bandpass filters, hot (heat reflecting) mirrors and optical attenuators were selected for the LDEF mission.

OPTICAL HARDWARE OF INTEREST

Glasses [UV-VIS-IR]

Aluminosilicate, borosilicate, lead silicate, potash borosilicate, SiO₂, soda lime silica, soda potash lime, titanium silicate, 12-UV transmissive windows [includes controls, MgF₂, Sapphire (Al₂O₃), CaF₂, LiF, SiO₂], black glass [low scatter], CaF₂, CdTe, Ge, SiO₂, Si, KRS-5, KRS-6, ZnSe, BaF₂, MgF₂, Al₂O₃, Corning 7940, Suprasil W, Ge (polycrystalline, high purity)

Filters [UV-VIS-IR]

CdSe, Ge, PbTe, PbF₂, KRS-5, SiO, ZnSe, ZnS, Cryolite on SiO₂, PbF₂ on SiO₂, MgF₂ on SiO₂, SiO on SiO₂, Ag on SiO₂, ThF₂ on SiO₂, ZnS on SiO₂, AR coating on MgF₂, assorted optical bandpass between 0.3 and 1.1 microns [Schott glasses], Al on SiO₂, neutral density [manufacturer: Corion], narrow band [Corion], hot mirrors [Corion, visible transmitting], Lyman alpha and 1600 angstrom UV filters, Al₂O₃ on SiO₂, Magnesium difluoride on SiO₂, assorted filters [mfr: OCLI], SiO on SiO₂, SiF₁₂ on SiO₂, Ge on SiO₂, Ag on SiO₂

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OPTICAL HARDWARE OF INTEREST (cont'd)

Paints and thermal control coatings make up the next category. Also included in this list are paints and other surface preparations used directly on the LDEF structure.

OPTICAL HARDWARE OF INTEREST (contd)

Paints/thermal control coatings

Chemglaze A-276 on Al, Zinc oxide-silicate [Z-93] on Al, Cnemglaze Z-306 on Al, Chemglaze [black] on graphite epoxy [Gr/Ep], Zinc oxide-silicone [S-13GLO] on Al, S-13GLO on Gr/Ep, Zinc orthotitinate-silicate [YB-71] on Al, Chemglaze 9924 primer, Chemglaze Z-302 on Al, Ben Har acrylic, 3M 401 C10 [black], 25 other surfaces in an active experiment, D-111 [black], Ag backed Teflon, Zinc orthotitinate [ZN2 TiO4, IITRI (white)], DC92-007 [white], PV100 ML101 [white], Sperex AP-101 [white], Sperex AP-102 [black], TiO2 Me Si ML101 [white], alpha Al2O3 Me Si ML101 [white], EU2O3 Me Si ML101 [white], JB-1 on Ta [black], NS43G #MM/GSFC [white], Catalac flat black paint, PV100 with silicone-alkyd binder [white], Chemglaze II A 571 [red], S2 [ASTRAL/CNES (black)], P 123 [ASTRAL, primer], PSG 120 FD silicone paint [CNES-ASTRAL (white)], PSZ 184 silicate paint [ASTRAL], Zinc chromate primer, MS-74 [white], Polymer films [Kapton, Kynar PVF2]

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OPTICAL HARDWARE OF INTEREST (cont'd)

Metal films (in most cases laid down on quartz substrates) and surfaces of metal solids (including assorted aluminum and stainless steel alloys) make up this category of LDEF hardware. Many of these materials are made available from the LDEF structure.

OPTICAL HARDWARE OF INTEREST (contd)

Metal films [substrates specified if known]

Indium oxide [In₂O₃], Aluminum oxide, Au plated Al [2024-T351], Au plated Al [6003], Au on SiO₂, Ir on SiO₂, Nb on SiO₂, Os on SiO₂, Pt on SiO₂, Cu on SiO₂, Ag on C, Ag on SiO₂, Ta on SiO₂, W on SiO₂, Sn on SiO₂, Zn on SiO₂, OSR mirrors [Au, Al, Ag]

Metal surfaces [self-supporting: includes mirror and diffuse surfaces]

Chromic acid anodized Al [low, med and high emmissivity], sulfuric acid anodized Al, Ni plating [on ?], LDEF structure [numerous possibles], stainless steel [asst: 303, 307, 327, 500], aluminum alloy [asst: 2014-T6511, 5056-H39, 2024-xx, 6063-T52, 6061-T651, 7075-T6], alodyne on Al, Mo mirror [coated and uncoated], diamond turned Cu mirror

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OPTICAL HARDWARE OF INTEREST (cont'd)

Optical sources range from a flashlamp to a CO₂ laser and nearly everything between. Detectors fall into several categories, including photovoltaic, photoconductive and pyroelectric types with several examples of each.

OPTICAL HARDWARE OF INTEREST (contd)

Optical sources

CO₂ waveguide laser, Nd+:YAG laser [glass rod], HeNe laser, laser diodes [AlGaAs and an array], flash lamp, 3-GaAs LEDs [830nm nominal], one sealed emitter module [1300nm], pre- and non-irradiated LEDs [probably 830nm, GaAs]

Optical detectors

Si and UV-enhanced Si [PIN], PMT [UV response], pyroelectrics [lithium tantalate (LiTaO₃), strontium barium niobate (SBN), triglycine sulfate (TGS)], numerous photovoltaics [Si, PbSnTe arrays, GaAsSb, HgCdTe, InSb], various photoconductors [HgCdTe, PbS, PbSe], solar cells [including CuINSe₂ and other thin film types], numerous solar cells [Si based] were flown in the Advanced Photovoltaic Experiment, GaAs and GaAlAs/GaAs solar cells, at least one channeltron array [original (trademarked) name for a micro-channel plate (MCP)], pre- and non-irradiated photodiodes

OPTICAL HARDWARE OF INTEREST (cont'd)

Optical fibers of various types (e.g. step and graded index) were flown on LDEF. Most, if not all, of these were multimode and therefore low bandwidth or short haul types

OPTICAL HARDWARE OF INTEREST (contd)

Fiber optics

Numerous fibers [nominally 10, silica core, unknown core diameter; reportedly, both step and graded index types] with various cladding materials from the Fiber Optic Data Transmission Experiment, one fiber of unknown type/composition from the Space Environmental Effects experiment, 4 multimode silica core fibers and 4 fibers of unknown material/modality [but probably silica core, multimode] from the Space Environment Effects on Fiber Optics Systems experiment

SELECTION CRITERIA/RATIONALE

This chart briefly describes some of the areas of interest for the different categories of optic hardware

From a system point of view, degradation of thermal control surfaces and painted baffles leads to both reduced baffling efficiency and deposition of particulates onto optical elements. Degradation of an optical surface due to exposure, combined with particulate deposition causes a loss of light transmission (or reflection, if a reflecting optic) and a loss of image quality (e.g. a sensor system).

When fiber optics are exposed to radiation (gamma and gamma-dot) they tend to become darker (less transmissive). Since signal level of a system is determined through a set of tradeoffs, this darkening can either reduce the available bandwidth (frequency response) or increase the number of errors generated, or both. Degradation of semiconductor sources and receivers due to radiation will compound these system related problems.

SELECTION CRITERIA/RATIONALE

Degradation of transparent elements (darkening, contamination)

- Diffuse scatter increase reduces throughput of light for imaging systems
- Degrades image resolution

Degradation of diffuse paints or metals (erosion, discoloration)

- Baffling efficiency decreased due to increase in specular reflection
- Redeposition on other materials
- Contamination of systems optics

Fiber optic darkening

- Loss of signal
- Increase in system BER
- Reduced bandwidths

Semiconductor detector changes

- Responsivity
- Detectivity
- Rise time (system bandwidth)

STATUS/FUTURE ACTIVITIES

Detailed lists of LDEF optics hardware have been obtained and are being consolidated in a database. The database is also being filled with information pertaining to PI test plans and tests which the SSIG desires, which will allow us to generate a testing matrix. A review of IDA's document of LDEF importance to SDI has been made and reviews of preliminary PI test results are continuing. Discussions with PIs are in progress to determine as much as possible about their test plans (e.g. - do they have controls, what tests are planned, is destructive testing planned, how will their data be formatted, what test they will definitely not perform due to insufficient funds or facilities, will test documents be available to the SSIG).

STATUS

- Detailed list of Optics hardware flown on LDEF completed
- Ongoing discussions with PI's regarding their test plans
- Initiated matrix of PI's test plans vs System SIG desired testing
- Review of preliminary PI test results

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Thermal

Dr. Wally Plagemann

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Preliminary Findings, Thermal

The following chart summarizes preliminary findings within the Thermal discipline. The majority of the Thermal section describes the status in determining durability of silverized teflon and chromic acid anodize coatings. These evaluations were performed at Boeing with funding provided by the Materials SIG.

Preliminary Findings, Thermal

- **On orbit contamination changed optical properties of thermal control coatings from their pre-flight values. UV and/or atomic oxygen (AO) exposure further contributed to these changes.**
- **White thermal control paints exposed to UV darkened due to changes in the paint binder. This resulted in dramatic increases in a/e. The same white paints exposed to AO and UV remained white since the AO removed the binder. These specimens generally became more diffuse.**
- **AO induced erosion of thermal control coatings occurred at incident angles up to 100 degrees.**
- **Preliminary analysis has shown that space end exposure (maximum UV exposure) resulted in a slight decrease in the chromic acid anodizing thickness.**
- **The long term exposure of CAA aluminum to the LEO environment caused a slight increase in the a/e. Future activities will determine if these changes were a result of contamination or an actual change in the CAA.**
- **Solar absorptance and thermal emittance of the silverized Teflon blanket's were unchanged from pre-flight values. Specularity decreased for blankets exposed to AO. Leading edge recession rates of the Teflon was 15-20 microns.**
- **Surface temperatures were within pre-flight design goals. LDEF interior saw benign temperatures throughout flight.**

Chromic Acid Anodized Aluminum Thermal Control Coatings

LDEF offers a unique opportunity to evaluate the performance of the chromic acid anodized aluminum after prolonged space exposure. The constant orientation of LDEF relative to the RAM direction throughout its entire mission has resulted in a unique distribution of exposure conditions. Since the tray clamps were positioned uniformly around the satellite, they represent every possible environmental exposure condition to both atomic oxygen and ultraviolet flux. They should, therefore, provide a complete picture of the combined space effects on the performance and durability of the chromic acid anodized coating. With this in mind, the objective of these analyses was to characterize the performance of the anodize coating as a function of space environmental exposure.

Space Environmental Effects on the Integrity of Chromic Acid Anodized Coatings

Objective:

Characterize performance of the anodize coating as a function of space environmental exposure

Tests to Date:

- Specular and diffuse reflectance
- Surface analysis
- SEM and metallography
- Absorptance and emittance

The tray clamps were anodized prior to flight to achieve an α/ϵ ratio of 2.1 ± 0.2 . The stability of this ratio is measurement of the durability of the coating and an indication of its effectiveness in thermally protecting the spacecraft. Since the effects of long term space exposure on the survivability of the anodize coating is an important parameter to be considered by designers of future low earth orbit spacecraft, considerable effort has been expended to analyze the absorptance and emittance of as many clamps as possible. To date ninety-eight clamps have been evaluated. There was not, however, a suitable population of non-flight control specimens. Only one non-flight control has been tested for comparison. Three other ground control clamps are available and will be tested. Fortunately, the reverse side of each clamp did not see the effects of space exposure. This afforded us a built in control for each clamp. The fact that the α/ϵ values for the exposed and nonexposed sides of each clamp could be compared allowed us to conduct a meaningful paired "t" analysis on the data to determine the statistical significance of the results.

Solar Absorptance and Emittance

Data points have been collected which represent all of the possible exposures to which LDEF was subjected. As seen in Table II, one of the main thrusts thus far has been comparison between the earth and space end exposures with over 1/3 of the samples analyzed coming from these two areas. The data indicates that there was a considerable difference in the percent change in the α/ϵ ratio between the two populations with the space end increasing by 6.1% while the earth end samples increased by only 1.5%. This indicates that UV exposure may have an adverse effect on the integrity of the anodize layer.

All of the average ratios from both the exposed and reverse sides of the clamps still fell within the range initially specified prior to flight and that the total average change thus far was only 4.8% for all samples tested. The differences noted however are real and are statistically significant at the 99% confidence level. All available tray clamps should be made available for absorptance and emittance testing to provide the largest possible data base to ascertain the relationship between the magnitude of these changes and the position on LDEF. Tests will also be initiated to determine if the observed result are related to space exposure or contamination effects.

While the differences observed thus far are relatively small it is unknown what effect longer exposures will have on the changes in optical properties. Assuming that the observed changes were induced by space exposure, they could have already reached their maximum levels and will now be constant with time or they could be following an Arrhenius relationship and may increase with further exposure. This points out the need for future ground based simulation to attempt to duplicate these results and determine the effects of longer exposure on the performance of the coating.

Position	n	Ave Front	α / ϵ Back	Δ %
Earth	20	2.07	2.04	1.5
Space	19	2.26	2.13	6.1
Off-Trailing Top	5	2.26	2.13	6.1
Off-Trailing Keel	11	2.24	2.09	7.2
Trailing	12	2.29	2.11	8.5
Perpendicular	5	2.26	2.21	2.3
Off-Leading Top	12	2.17	2.09	3.8
Off-Leading Keel	8	2.23	2.06	8.3
Leading	6	2.18	2.15	1.4
Avg		2.20	2.10	4.8

α / ϵ For non flight
Control = 1.97

The metallurgical analysis has thus far been focused on the tray clamps associated with the copper grounding straps. These clamps offered the unique opportunity to evaluate areas on the same side of the clamp which were either fully exposed to the environment or protected by the grounding strap of the shims.

SEM and Metallography

Figure 5 contains photographs of the clamp from tray E-02-6. The areas on the clamp which were protected by the shim and the ground strap can be easily detected as lighter regions on the clamp surface. Obviously, contamination from external sources has contributed some of the discoloration on the exposed area. The role of UV and atomic oxygen exposure in this discoloration is being investigated.

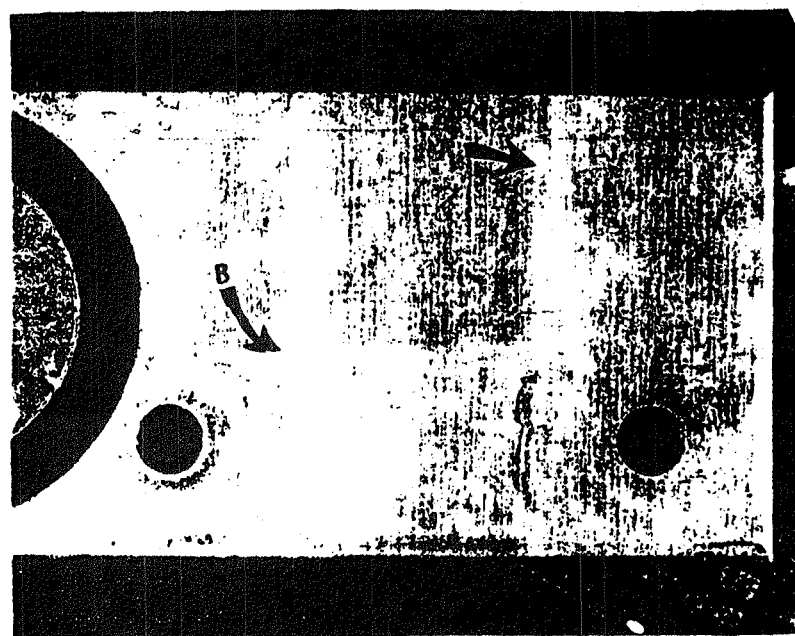
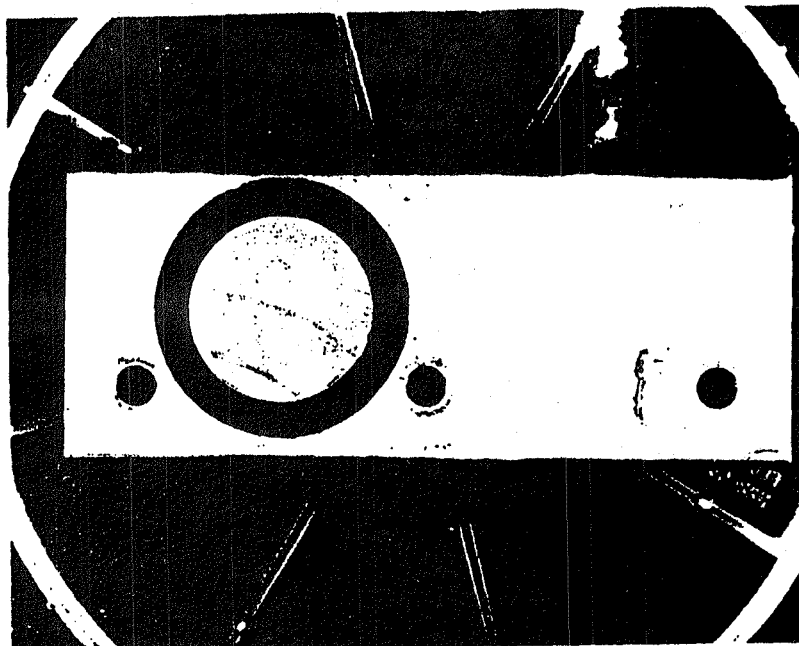


FIGURE 5. Photo macrographs of tray clamp E02-6 with arrows indicating boundaries between exposed regions and those protected by (A) the copper ground strap and (B) the aluminum shim.

Figure 6 contains photomicrographs of cross sections obtained from exposed and protected areas of tray clamps subjected to leading edge exposure (Figure 6 A&B from clamp E10-6) and trailing edge exposure (Figure 6 C&D from clamp E02-6). The most notable feature in these figures is what appears to be debris on the protected surfaces of the clamps.

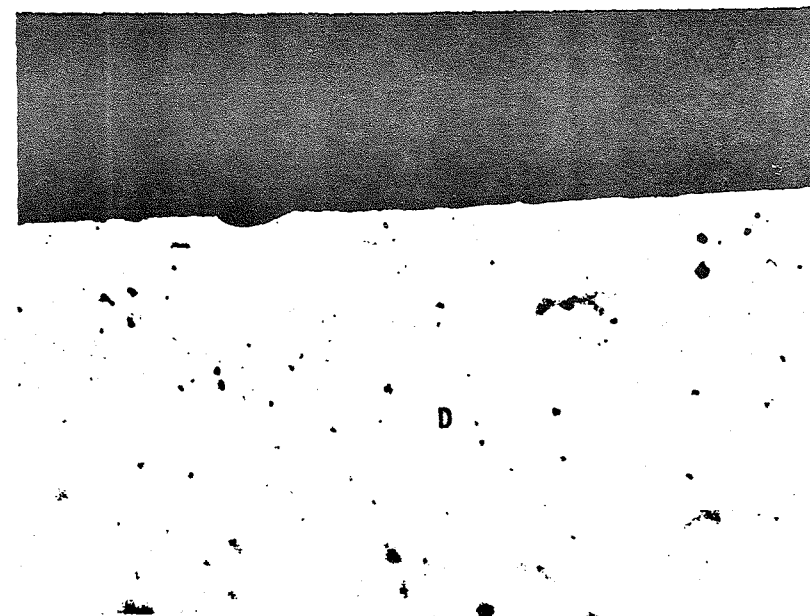
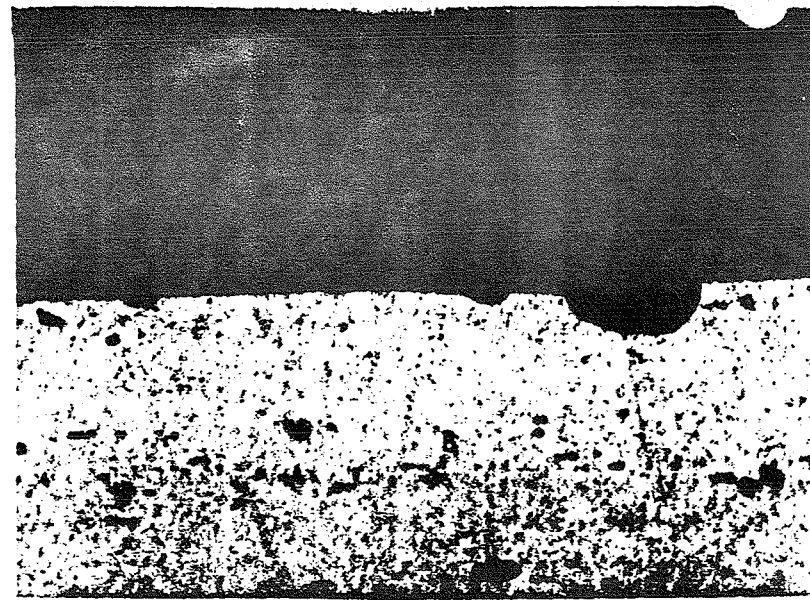
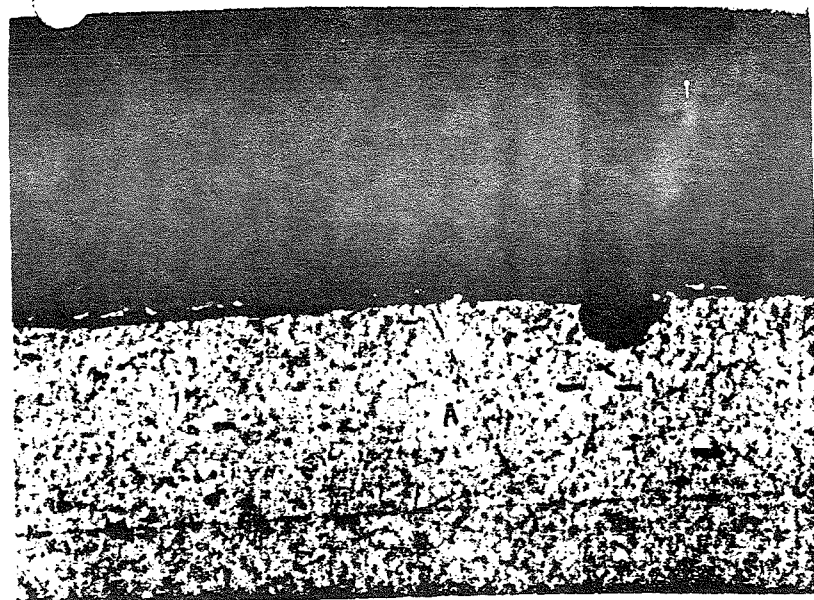
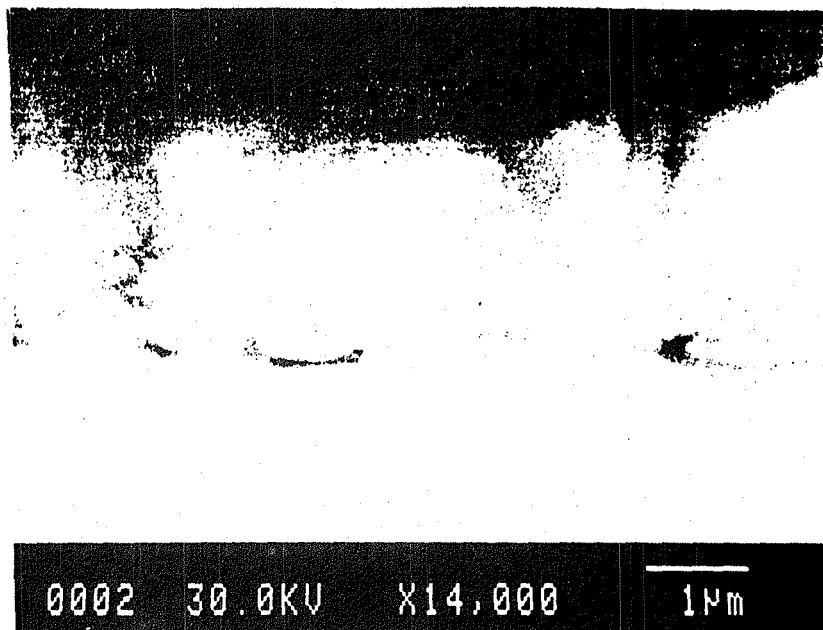
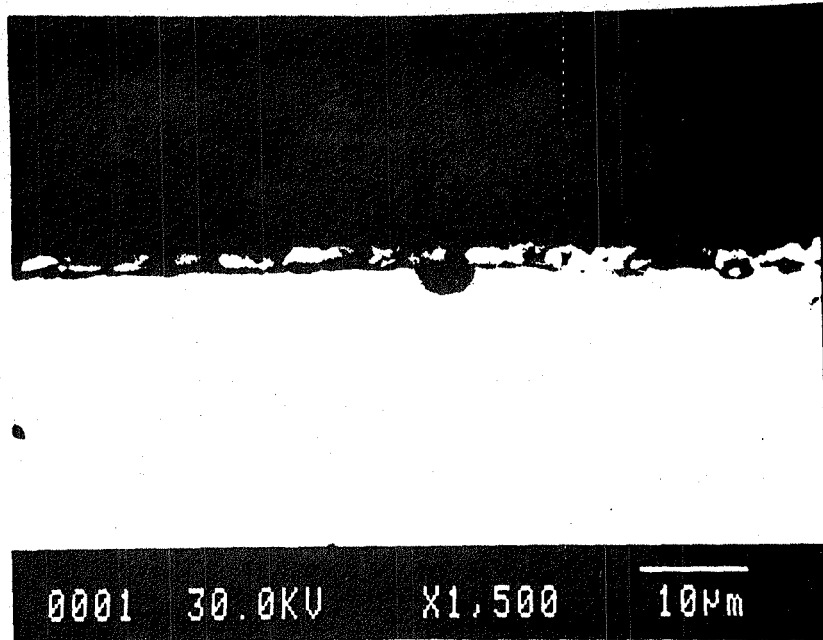


FIGURE 6. Optical photomicrographs at 1000X depicting (A) protected and (B) exposed regions from the surface of leading edge clamp E10-6 and from (C) protected and (D) exposed areas from trailing edge clamp E02-6.

SEM Photomicrographs revealed that what appeared to be isolated pieces of debris was actually a discrete layer on the surface of the clamp.



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FIGURE 7. Higher magnification scanning electron photomicrographs depicting the observed surface layer on the protected surfaces of tray clamp E10-6.

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OF POOR QUALITY

An EDX spectrum obtained from the layer of debris is presented in Figure 8. The data indicates that the material was comprised solely of aluminum, probably in the form of aluminum oxide. The exact source of this layer is not known at the present time. However, it is probably related to some smearing of the surface associated with the application of the anodize coating. Regardless of the source, Figure 6 indicates that it is absent from the areas of the clamp that were exposed to the space environment. This indicates that oxidation of the surface has occurred as a result of exposure.

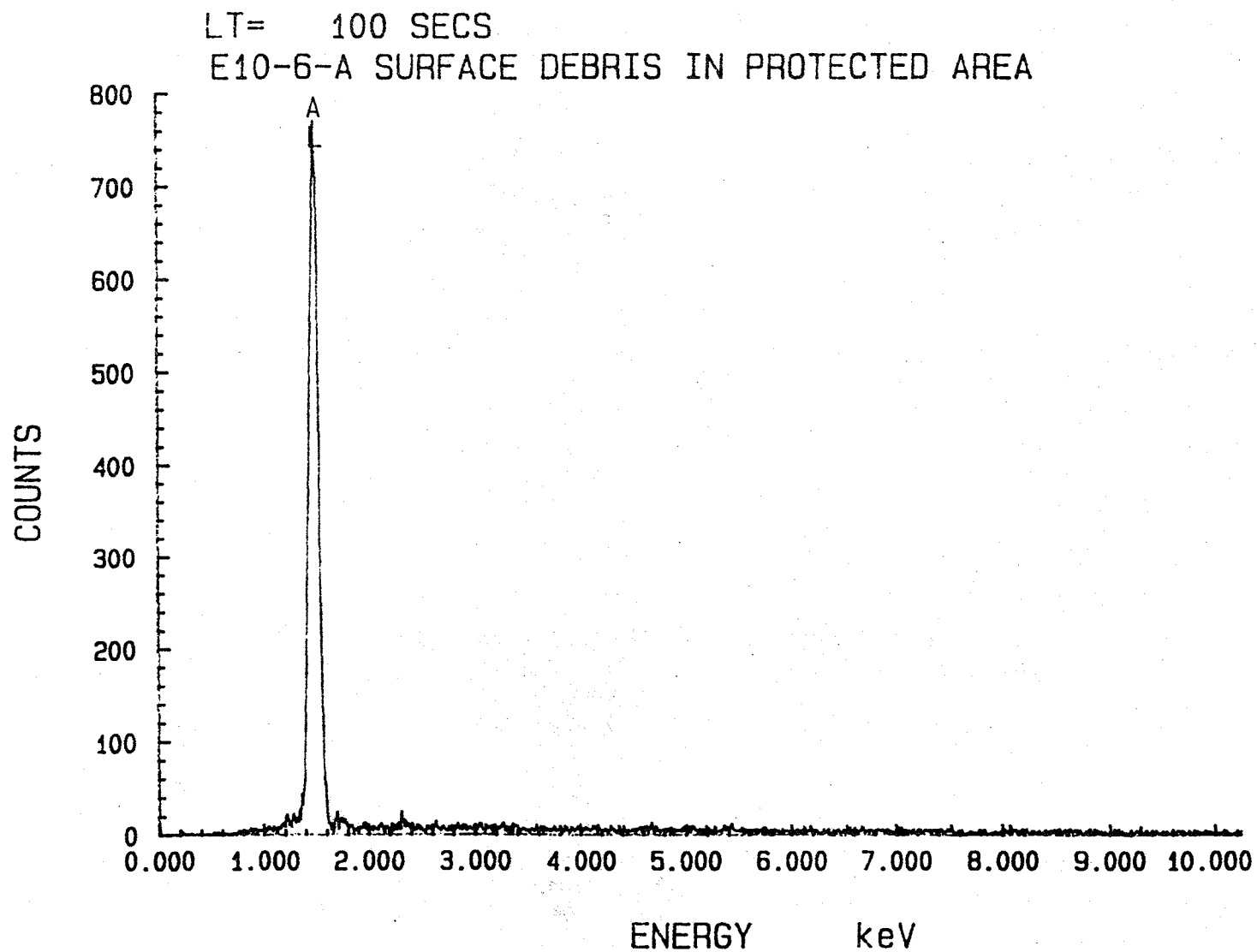


FIGURE 8. EDX elemental spectrum of surface layer observed on protected surface of tray clamp E10-6

Figure 9 contains SEM photomicrographs of both exposed (Figure 9 A&C) and protected (Figure 9 B&D) areas from the surface of a trailing edge clamp, E-02-6. As seen in these figures the surface of the clamp appears to be moderately pitted and there is no significant variation in the amount of pitting present on the exposed or protected surface.

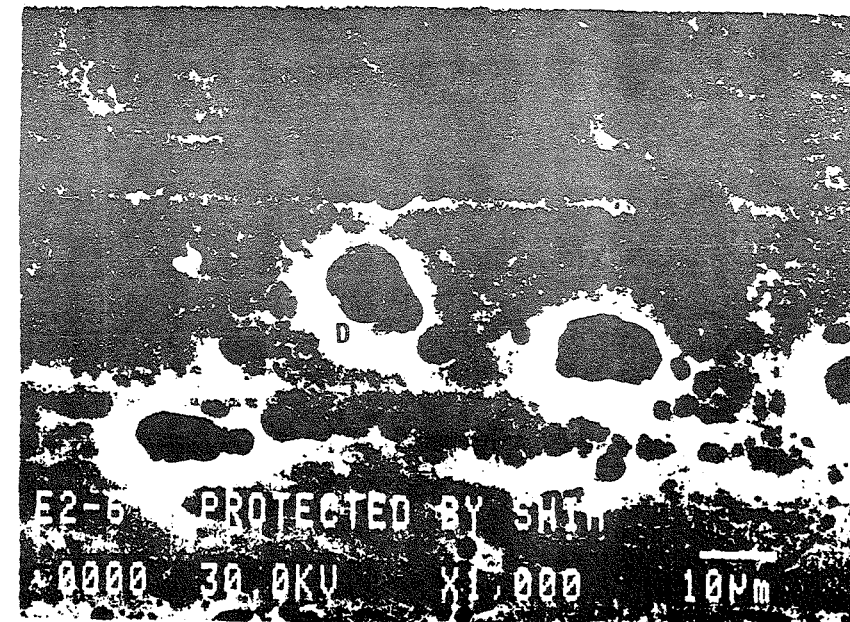
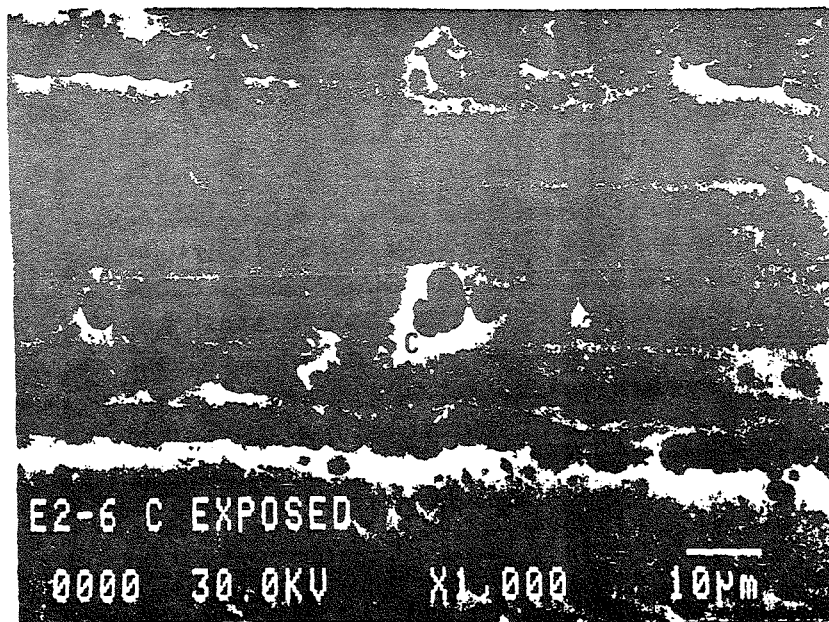
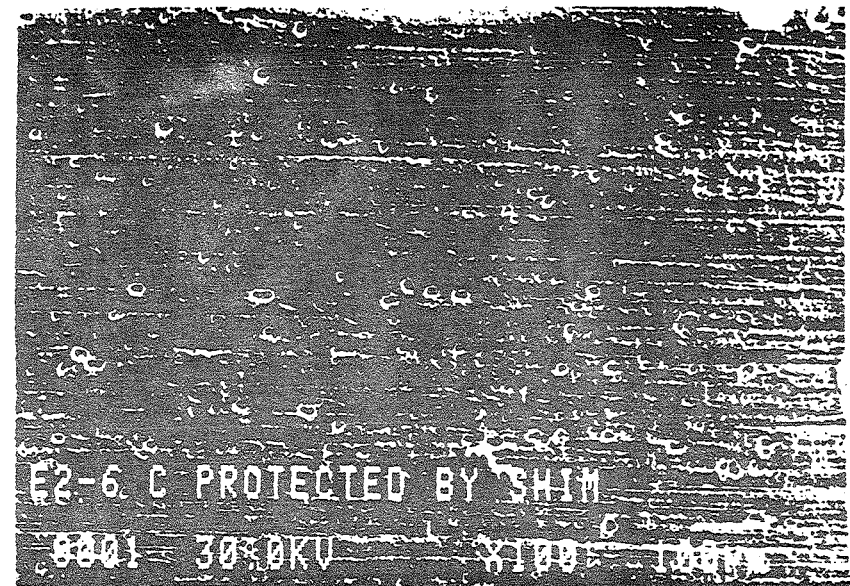
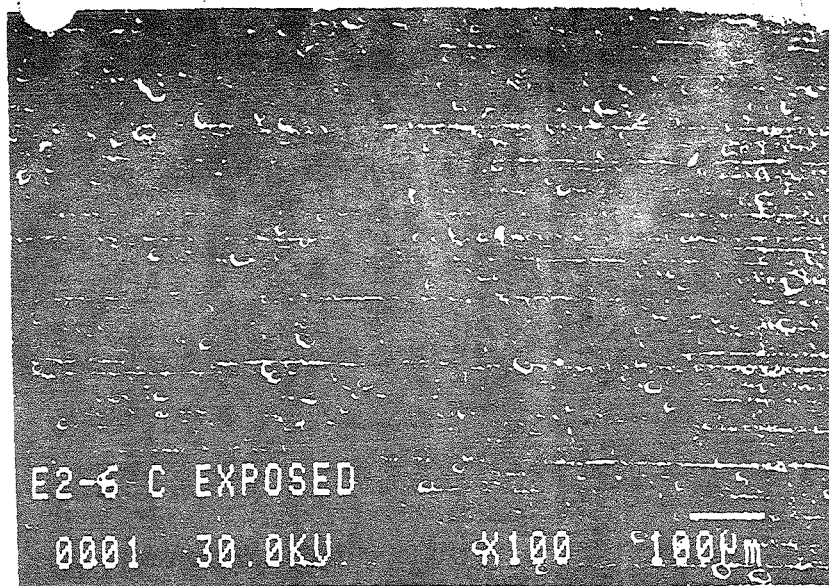


FIGURE 9. SEM photomicrographs depicting surface porosity on (A) exposed and (B) protected at 100X and (C) exposed and (D) protected at 1000X for trailing edge clamp E02-6. 183

Figure 10 contains SEM photomicrographs of exposed (Figure 10 A&C) and protected (Figure 10 B&D) areas from a leading edge tray clamp, E-10-6. It should be noted that, while pits are also present in both the exposed and protected areas of the coating, the number of pits present on the exposed surface in this case is considerably greater than on the protected surface. Since the pits were observed on both the exposed and protected areas of the surface, coupled with the fact that their morphology was similar in both areas it has been concluded that their presence was probably the result of coating degradation as opposed to micrometeorite damage. The data obtained during the current analysis indicates therefore that leading edge exposure may degrade the anodize coating. Further testing in this area is needed, however. More clamps need to be analyzed to confirm these results. The metallurgical analysis should be conducted in conjunction with SIMS profiling to correlate observed degradation with coating thickness. Image analysis should also be employed to quantify the degree of pitting.

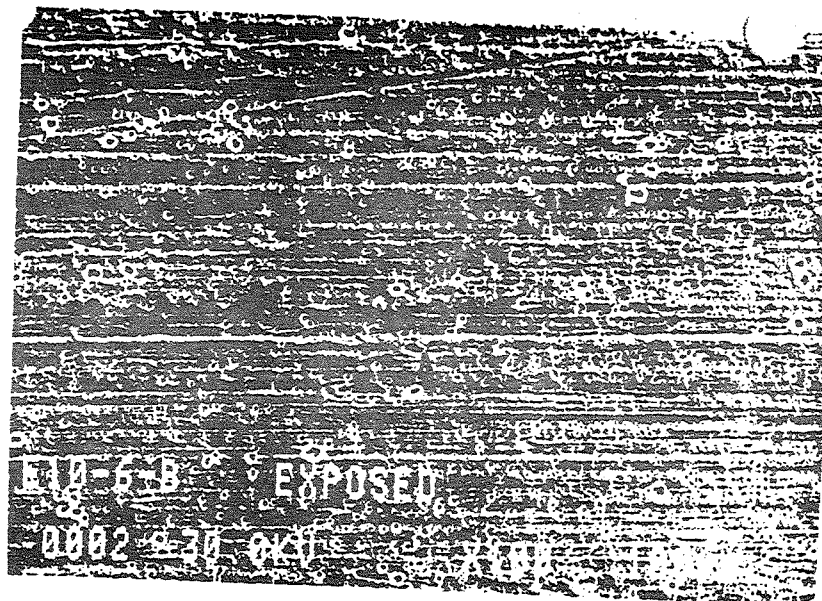


FIGURE 10. SEM photomicrographs depicting surface porosity on (A) exposed and (B) protected at 100X and (C) exposed and (D) protected at 1000X for leading edge clamp E10-6.

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CHROMIC ACID ANODIZED ALUMINUM CONCLUSIONS

- Spectroscopic anomalies on tray clamps appear to be random and unrelated to exposure or position on LDEF
- Surface analysis indicated that space end exposure resulted in a decrease in CAA thickness
- Metallurgical analysis indicated that leading edge exposure increased the porosity of the CAA 6061 aluminum
- Long term space exposure results in a slight increase of a/e of CAA 6061 aluminum

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Future Activities

- Tray Clamps
 - Complete optical and surface analyses
 - Correlate our test results with NASA measurements from CAA primary structure
 - Confirm metallurgical findings on coating porosity
 - Scanning Transmission Electron Microscopy (STEM)
 - CAA thickness evaluation

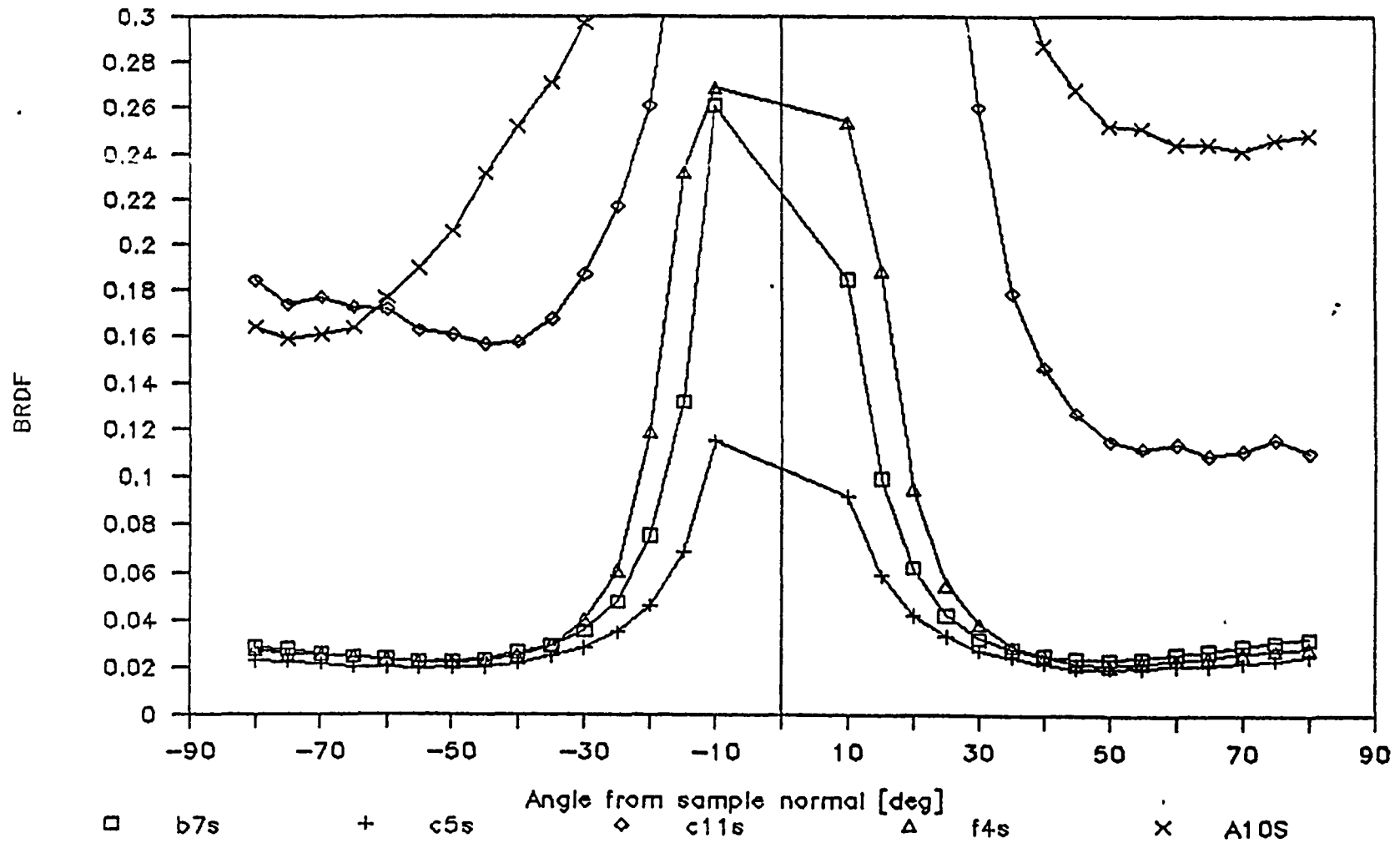
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Optical Properties of Ag/Teflon

The solar absorptance and thermal emittance of the Ag/Teflon specimens tested to date show minimal changes. However, the diffuse reflectance of the Ag/Teflon exposed to atomic oxygen showed a large increase. This chart shows bidirectional reflectance distribution function (BRDF) curves for five specimens from trays located throughout LDEF. The closer the tray to the leading edge, the larger the increase in diffuse reflectance. The asymmetry in the curves is likely due to the anisotropy of the exposed Teflon surface.

BRDF of Ag/Teflon LDEF Samples

Comparison of exposed Ag/Teflon for five different locations



Ag/Teflon Recession Measurements

Pre-flight (as manufactured) thickness of the first surface Teflon layer varied between 0.004" to 0.006", making determination of the recession caused by the long term exposure to the LEO environment difficult. Three techniques have been used to measure recession. Weights of known areas were obtained for pairs of specimens, one from an exposed area and one from a nearby shielded area. The recession was then calculated from weight differences. These differences turned out to be within the variation possible given the material specifications, making this approach unsuitable. The second method was the examination of photomicrograph cross-sections to determine the thickness directly. The third technique was to locate particulate contaminants which protected the Teflon directly underneath. Using the protected location as the reference height, the depth of erosion was measured at sites adjacent to the protected area. This involved searching the surface with a microscope to find a protected site and measuring the depth change required to bring an adjacent eroded area into focus. The following chart shows the various recession of the Teflon vs tray location. The range of calculated recession rates (volume of Teflon recessed/calculated atomic oxygen fluence for that specific location) from all individual measurements to date is 0.05 to 0.38×10^{-24} cm³/atom. The variation in measured recession rates reflects the as manufactured thickness variations, the potential that specimens thought to be shielded may have received considerable atomic oxygen fluence, and that areas near the edge of exposed surfaces may have received enhanced fluence due to secondary scattering from nearby surfaces.

The following chart shows exposed and shielded thickness of the Teflon for eight different locations on LDEF. These thicknesses were determined using the "third" technique.

Specimen Tray Location	Thickness (mils)	
	Exposed	Shielded
C11	4.6	5.0
D11	4.4	5.2
A10	4.1	4.7
D7	4.8	5.0
C6	5.3	5.0
B5	5.2	5.4
A2	5.3	5.1
D1	5.2	5.4

- Specimens exposed to atomic oxygen show recession
- Specimens not exposed to atomic oxygen reflect variability in initial thickness of FEP

Thermal Control Coating Disks

Thermal control coating disks consisting of Chemglaze A276 white paint and Chemglaze Z306 black paint were placed on tray clamps throughout LDEF. One of the major activities being undertaken at Boeing is to characterize the changes which have occurred with these coating disks as a function of their specific space exposure. The following status chart summarizes the analysis of these disks.

THERMAL CONTROL COATING DISKS

- **Atomic oxygen induced erosion effects are apparent to an incident angle of 100 degrees. Optical properties of leading edge disks are still nominatl, mechanical properties have degraded.**
- **Darkening of trailing edge white paint surfaces appears to be largely UV induced degradation of the paint resin with some additional effect from degraded surface contaminants.**
- **To date, cross sectioning to determining erosion depths have been unsuccessful**
- **Surface analysis indicates the presence of a contaminant film containing fluorine and silicon**

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Batteries/Solar Cells

Dr. Chris Johnson

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BATTERY/SOLAR CELLS

A LiSO_2 Battery Distribution Plan was compiled by NASA-LaRC. Each investigator has signed a Memorandum of Understanding (MOU) with NASA-LaRC. In the MOU, specific tasks and areas of investigation are identified. We reviewed the MOUs and suggested the addition of glass-to-metal seal corrosion. In other programs, this unique problem has developed the time involving lithium attack of the glass used to seal and electrically insulate the negative terminal from the cell case. This type of corrosion can stress the glass to crack and allow electrolyte, sulfur dioxide, to diffuse out of the cell.

Solar cells from experiments on LDEF have been distributed to the responsible principal investigator for each experiment. A database is being compiled, which identifies the principal investigator and planned tests for solar cells and associated technologies, i.e., adhesives, coatings, cover glasses, and mechanical attachments. Investigators have been solicited to provide inputs for the data base to assure a complete overview of the tests and results.

Battery/Solar Cells

OBJECTIVE:

- Identify degradation modes of batteries and solar cells useful to future missions

BATTERIES:

- Distribution Plan Complete
 - LiSO₂ - Aerospace Corp 20
 - SAFT Corp 10
 - NASA LeRC 1
 - JPL (TRW) 3
 - Naval Weapons Lab 8
- LiCF - NASA-MSFC
- NiCd - NASA-Goddard
- Memorandum of Agreement signed with each investigator

SOLAR CELLS

- Distribution completed
- Testing and tasks being compiled into database

DATA ON LDEF BATTERIES USEFUL TO OTHER PROGRAMS

Lithium sulfur dioxide batteries are presently used on several space programs. These applications include: 1) Computer Memory Retention batteries for Boeing Inertial Upper Stage computers, 2) Primary batteries for Galileo mission, and 3) several SDI applications. The Li/SO_2 batteries have excellent capacity retention and can perform at temperatures as low as -40°C . Selection of the batteries for Galileo relied on the ability of the batteries to perform at low temperature and after long non-use times of transit. The use of Li/SO_2 batteries for speciality requirements of low temperature and long life will continue for many SDI programs. Information of the life expectancy in space use will aid these programs. Space use may result in less degradation than comparable earth storage, since the temperature environment in space can be at a lower nominal temperature. The lower temperature is expected to slow corrosion reactions believed to be responsible for leakage failure modes.

Lithium carbon monofluoride (LiCF) batteries are of interest since they represent the chemistry used in the Shuttle booster batteries: 1) command destruct, 2) Frustrum location Aid, and 3) Payload Package. Batteries using this chemistry are also planned for the CIRRUS flight and SDI applications requiring low rate discharge.

Nickel cadmium batteries have been and are being used on a variety of remote sensing and science related satellites operating in low Earth orbit.

Data on LDEF Batteries Useful to Other Programs

LiSO₂ - Batteries

- **Boeing IUS - Computer Memory Retention Battery**
- **Galileo - ~ 8Ah batteries (multiple cells)**
- **SDI Application**

LiCF - Batteries

- **CIRRUS - 25Ah cells planned for batteries**
- **Shuttle Booster - command destruct batteries**

NiCd - Batteries

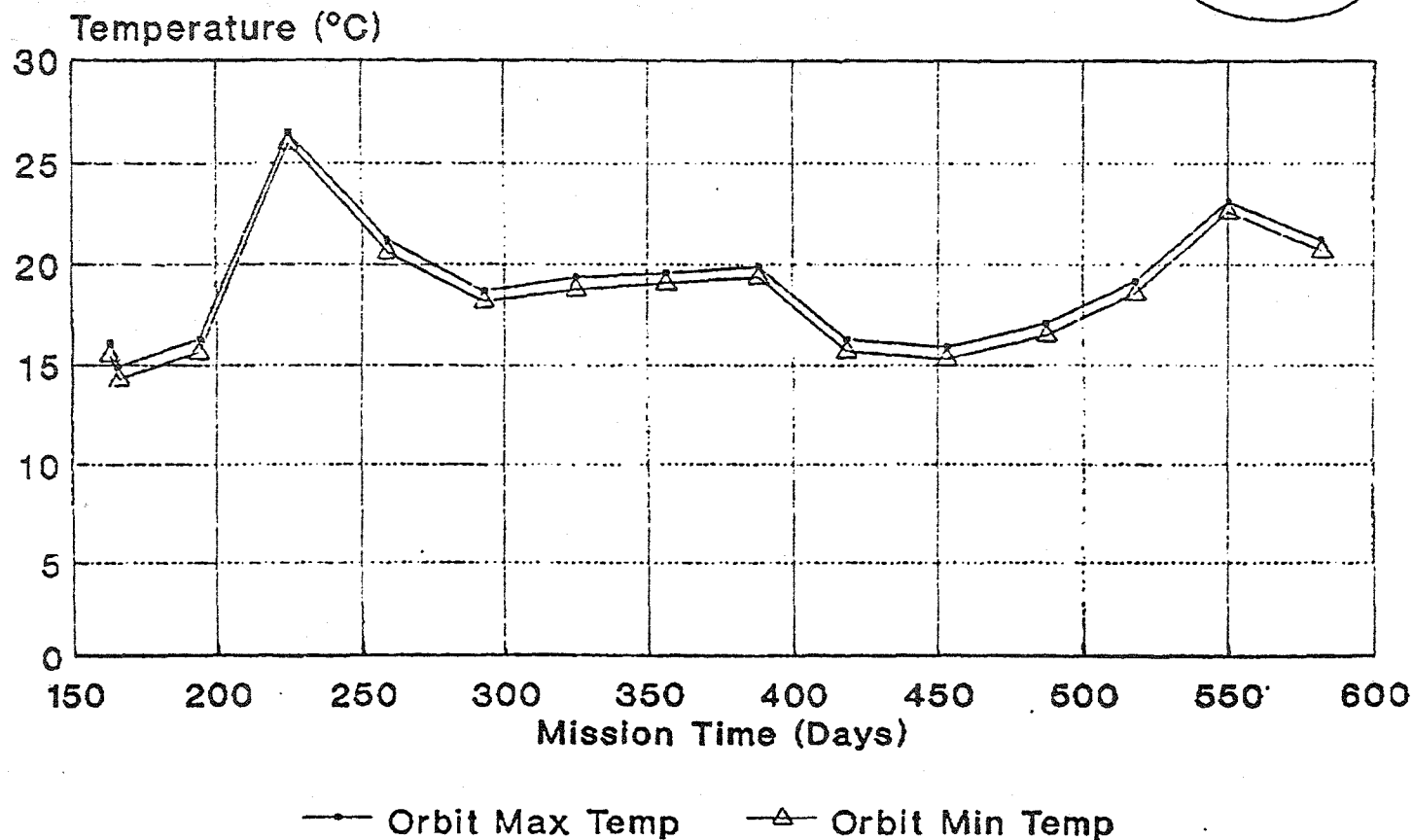
- **Wide variety of remote sensing and science satellites**

PRELIMINARY DAILY FLIGHT DATA

This chart shows the temperatures of one of the batteries powering experiment S0069. The change in temperature was minimal indicating a benign environment for the batteries. The lithium batteries would be expected to perform well at these temperatures and would experience a minimal degradation.

PRELIMINARY TCSE DAILY FLIGHT DATA

Battery #2 Temperature



d1d082

STATUS OF BATTERY EVALUATION

One Li/SO₂ battery appears to have leaked. This battery was on Experiment #AO187-1. Sulfur dioxide, the active cathode electrode constituent of the cells, was detected when the battery test port was opened. One cell of the battery exhibited a low open circuit voltage typical of a depleted cell. The suspect cell has been sent to the original battery manufacturer, SAFT, for internal analysis.

A discoloration was detected adjacent to the battery on the panel (note picture on next page). Chemical analysis of the deposit indicated an absence of sulfur. Since the sulfur dioxide was only detected upon opening the test port and the deposit lacks sulfur compounds, it is concluded that the battery cell leakage was contained by the battery case. Additional information on the cell leakage will be available from the autopsy at SAFT.

On experiments #S0069 and #S1005 an odor was detected on opening the battery port. The odor was characteristic of the dimethyl sulfite electrolyte used in the carbon monofluoride batteries of these experiments. More data will be provided from cell autopsy planned at NASA-MSFC.

SAFT, under funding by the System SIG, has begun characterization of the ten LiSO₂ batteries distributed to them. These ten batteries possess various states of charge, ranging from near 100% to fully depleted. Characterization has included: weights, X-ray, electrical, and opening of individual cells. All results, to date, are nominal. SAFT's final report is expected in March.

Status of Battery Evaluation

Experiment #A0187-1

- **S0₂ detected when battery test port opened**
- **One cell of 7.5V battery had low voltage**
- **Suspect cell to be sent to SAFT for autopsy**
- **Discoloration detected outside battery case**
 - **Chemical test indicate absence of sulfur**
 - **Indications - no S0₂ outside battery case**

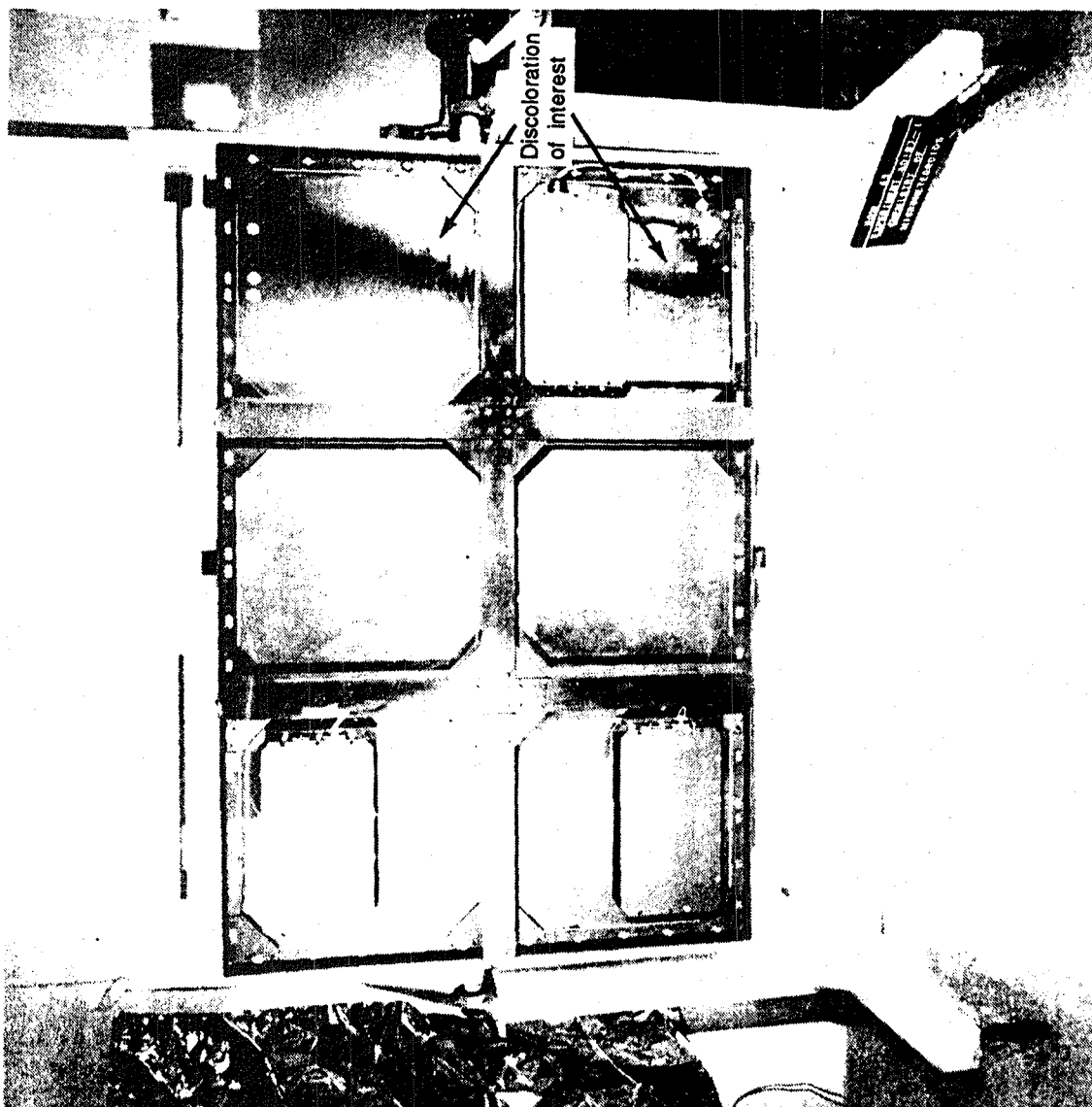
Experiment #S0069 and #S1005 (LiCF Batteries)

- **Odor detected when battery case opened**
- **Cells autopsy planned at NASA-MSFC**

SAFT evaluation of LiSO₂ batteries

- **SAFT is mfg of all LiSO₂ batteries flown on LDEF**
- **To date, no anomalies have been found**

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FOLLOW ON ACTIVITIES

Battery distribution has been completed. Investigators have agreed to measure the capacity remaining in some of the battery cells to determine the state of charge. Some cells will be cut open to evaluate internal corrosion, which could indicate potential leakage problems. The glass-to-metal seal will be investigated for evidence of lithium attack and glass cracking.

The solar cell data base will continue to grow as more experimental results are compiled. Information common to several investigators will be accumulate to indicate possible trends in degradation of the solar cells during space exposure. A surface analysis experiment is being proposed by Boeing to identify degradation due to phases of space exposure and earth handling. The surface analysis techniques used at Boeing to characterize the normal deposits seen on LDEF structure can be used as a baseline to compare those observed on LDEF solar cells. Additional migration of contamination into the solar cell structure would be analyzed using a sensitive electron microprobe technique. Improved estimates obtained for degradation factors of solar cells would be useful for all space power applications using solar panels.

The preliminary conclusions of the battery leakage analyses indicate that none of the batteries experienced external leakage, however some odors detected indicate internal cell leakage may have occurred. The battery case integrity contained the odors and prevented electrolyte from damaging hardware on LDEF.

Follow On Activities

- **Battery Distribution Completed**
 - **Residual capacity remaining**
 - **Evidence of degradation - corrosion and glass seal integrity**
- **Solar Cells - Compiling database of experiments and investigator/tasks. Design experiments to identify solar cell contamination from space exposure versus earth and recovery**

Preliminary Conclusions:

No evidence of leaky or failed battery in flight

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